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RESEARCH MEMORANDUM

INVESTIGATION OF PERFORMANCE OF TURBOJET ENGINE WITH CONSTANT- AND VARIABLE-AREA EXHAUST NOZZLES

By Lewis E. Wallner

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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INVESTIGATION OF PERFORMANCE OF TURBOJET ENGINE WITH CONSTANT- AND VARIABLE-AREA EXHAUST NOZZLES

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SUMMARY

The performance of a turbojet engine with constant- and variable-area exhaust nozzles has been investigated in the NACA Cleveland altitude wind tunnel. The investigation was made at simulated altitudes from 5000 to 45,000 feet and simulated flight Mach numbers from 0.12 to 0.94.

The efficiency of the variable-area exhaust nozzle was from 1.5 to 8 percent lower than the efficiency of the constant-area nozzle. As a result, the net thrust obtained with the variable-area nozzle at an altitude of 25,000 feet, a flight Mach number of 0.53, and a turbine-outlet temperature of 1600° R was 8 percent lower than that obtained with the constant-area nozzle. At the same flight conditions and a net thrust of 1200 pounds, the specific fuel consumption was 8 percent higher with the variable-area nozzle than with the constant-area nozzle. With the results corrected to a nozzle efficiency of 100 percent, approximately the same thrust and specific fuel consumption were obtained at limiting engine conditions for the variable- and constant-area nozzles. Reducing the thrust by decreasing the engine speed with the constant-area nozzle or by increasing the nozzle area with the variable-area nozzle resulted in about the same specific fuel consumption.

At an altitude of 25,000 feet and a flight Mach number of 0.53, a 33-percent increase in nozzle area decreased the thrust about 47 percent. An equal thrust reduction with the constant-area nozzle, required an estimated reduction in engine speed from 12,350 to 10,500 rpm.

INTRODUCTION

Because of the degree of thrust control that can be exercised at constant rotational speed with an engine equipped with a variable-area exhaust nozzle, the performance characteristics of such an engine configuration are of great interest. Several operational problems would be relieved by regulating the thrust with a variable-area exhaust nozzle instead of changing the engine speed. One problem is the time required to change engine thrust. Because of the relatively high inertia of the rotor, considerable time is needed to accelerate or decelerate the engine. With a variable-area nozzle, however, rapid changes in thrust can be effected by varying the nozzle area. Another problem that might be alleviated is combustion blow-out, which is often encountered at reduced thrusts obtained at low engine speeds with a constant-area nozzle. With a variable-area nozzle, reduced thrusts can be obtained at high engine speeds by opening the exhaust nozzle.

An investigation of constant- and variable-area exhaust nozzles on a turbojet engine was made in the NACA Cleveland altitude wind tunnel during July 1947. Engine performance with the two nozzles was obtained for a wide range of flight conditions. A comparison of engine performance with each type of exhaust nozzle was then made on the basis of net thrust and net thrust specific fuel consumption. An analysis of the experimental results and a tabulation of the basic performance data are presented.

ENGINE AND INSTALLATION

An early experimental Westinghouse 24C turbojet engine mounted in a wing nacelle was installed in the altitude-wind-tunnel test section (fig. 1). The engine consists of an 11-stage axial-flow compressor, an annular-type combustion chamber, and a two-stage turbine. For the first part of the investigation, the engine was equipped with an exhaust nozzle having a constant area of 1.187 square feet. This nozzle area was so selected that a turbine-outlet temperature of 1600° R would be obtained at rated engine speed and sea-level static conditions. For the second part of the investigation, the engine was equipped with a variable-area exhaust nozzle with which the projected-outlet area could be varied from 1.017 to 1.885 square feet. The variable-area nozzle was the clam-shell type, with pivot points at the top and the bottom of the tail pipe (fig. 2). A movable motor-driven yoke was used to change the nozzle area. Flexible steel sealing strips were installed on the front of the movable lip to minimize gas leakage (fig. 3). Detailed temperature and pressure surveys were obtained at six measuring stations in the engine, as shown in figure 4.

Dry refrigerated air was supplied to the engine through a duct from the tunnel make-up air system (fig. 1). The pressure and the temperature at the compressor inlet (based on 100-percent ram-pressure recovery) were maintained at values corresponding to flight conditions in NACA standard atmosphere and the static pressure in the tunnel test section was maintained at the desired altitude value.

Engine thrust was obtained from measurements made with the tunnel balance scales. Engine air flow was calculated from values of pressure and temperature measured in the engine inlet duct (fig. 4, station 1).

PROCEDURE

The performance of an axial-flow turbojet engine was obtained in the altitude wind tunnel for the following simulated flight conditions:

Altitude (ft)	Flight Mach number
5,000	0.12
15,000	.53
25,000	.12
25,000	.25
25,000	.53
25,000	.73
25,000	.86
25,000	.94
35,000	.52
45,000	.52

With the constant-area exhaust nozzle, the engine was operated over a wide range of engine speeds. With the variable-area exhaust nozzle, data were obtained at engine speeds of 11,000, 12,000, and 12,500 rpm (rated engine speed) at four exhaust-nozzle-outlet areas for each engine speed.

The symbols and equations used to calculate the results are given in the appendix.

RESULTS AND DISCUSSION

In order to compare the engine performance with the two general types of nozzle, it is necessary to evaluate the effect of the nozzle losses. Experimental constant- and variable-area nozzle efficiencies presented in figure 5 for several flight conditions and engine speeds show that the variable-area nozzle used in this investigation was less efficient than the constant-area nozzle. Exhaust-nozzle efficiency, which is defined as the ratio of the measured jet thrust to the jet thrust obtainable with no tail-pipe or nozzle losses, was calculated by means of equation (3) (appendix). The efficiency with the constant-area nozzle was about 95 percent for all flight conditions and engine speeds, whereas the efficiency with the variable-area nozzle varied from 87 to 93.5 percent. The losses obtained with the variable-area nozzle are attributed to gas deflection and turbulence at the nozzle outlet, together with leakage through the nozzle seals.

The engine performance with the constant- and variable-area exhaust nozzles has been compared on the basis of 100-percent efficiency for both nozzles and on the basis of the nozzle efficiencies actually obtained.

Performance with 100-Percent Exhaust-Nozzle Efficiency

The variation of net thrust with turbine-outlet temperature and the variation of net thrust specific fuel consumption with net thrust are presented in figure 6 for constant- and variable-area exhaust nozzles (data corrected to nozzle efficiencies of 100 percent). Data are presented for several flight conditions at various engine speeds with the constant-area nozzle and at four nozzle areas for each of the three engine speeds with the variable-area nozzle. On the basis of equal exhaust-nozzle efficiency, about the same thrust and specific fuel consumption were obtained at corresponding engine speeds and turbine-outlet temperatures for both variable- and constant-area nozzles. Any slight differences at the same engine speed are due to experimental inaccuracies in the data.

At a given turbine-outlet temperature, increasing the engine speed with the variable-area nozzle sometimes decreased the net thrust (fig. 6(a)). A curve showing the variation of net thrust with turbine-outlet temperature does not, however, take account of the important parameter of exhaust-nozzle area. For example, at 12,000 rpm and a turbine-outlet temperature of 1122° R, the air flow was 28.26 pounds per second at a nozzle area of 1.487 square feet (table I, run 55; uncorrected values). At 12,500 rpm and at a turbine-outlet temperature of 1127° R, although the air flow did increase slightly to 28.60 pounds per second, the nozzle area was increased to 1.610 square feet (table I, run 59).

At an altitude of 25,000 feet, a flight Mach number of approximately 0.53, and a constant engine speed of 12,500 rpm, increasing the nozzle area from 1.211 to 1.610 square feet (33 percent) decreased the net thrust from 1378 to 738 pounds (46 percent). (See table I, runs 62 and 59.) In order to produce the same thrust decrease with the constant-area nozzle, an estimated reduction in engine speed from 12,350 to 10,500 rpm would be required. (See fig. 6(a).)

Effect of flight Mach number. - The effect of flight Mach number on net thrust and specific fuel consumption (fig. 7) for the variable- and constant-area exhaust nozzles, assuming 100-percent nozzle efficiency, was obtained by cross-plotting curves such as those presented in figure 6. It is a characteristic of this engine that an increase in flight Mach number reduced the turbine-outlet temperature obtained at any engine speed, whereas an increase in altitude at a given flight Mach number raised the turbine-outlet temperature. At high altitudes and low flight speeds, it was therefore impossible to obtain rated engine speed without exceeding the safe temperature limits of the engine. From a preliminary investigation of the constant-area nozzle at a flight Mach number of 0.25 and an altitude of 25,000 feet, a maximum turbine-outlet temperature of 1600° R was obtained at an engine speed of 12,080 rpm; at a flight Mach number of 0.94, a turbine-outlet temperature of 1570° R was obtained at 12,500 rpm. Consequently, at flight Mach numbers less than 0.80, the engine was limited by a turbine-outlet temperature of 1600° R (temperature obtained with the constant-area nozzle at sea-level static conditions) and at Mach numbers greater than 0.80, by an engine speed of 12,500 rpm. Because limiting temperatures could be maintained at rated engine speed for all flight Mach numbers with the variable-area nozzle, slight gains in thrust over that obtained with the constant-area nozzle are available at most Mach numbers. At a Mach number of about 0.80, at which limiting turbine-outlet temperature and rated engine speed could be obtained for the constant-area nozzle as well as the variable-area nozzle, the thrusts with both nozzles were approximately the same (fig. 7). The net thrust specific fuel consumptions obtained with the constant- and variable-area nozzles at maximum engine conditions were approximately equal for all flight speeds.

The variation of net thrust specific fuel consumption with flight Mach number is shown in figure 8 for three reduced values of net thrust. Thrust with the variable-area nozzle was reduced by increasing the nozzle area. Although most data with this nozzle were obtained at rated engine speed, in a few cases an engine speed of 12,000 rpm was used because a slightly lower specific fuel consumption was obtainable at the same thrust. At thrust values of

80 and 65 percent of the maximum available thrust, the specific fuel consumption was approximately the same for the constant- and variable-area nozzles at all flight speeds when compared at 100-percent nozzle efficiency. At 50 percent of the maximum available thrust, however, slightly lower specific fuel consumptions were obtained with the variable-area nozzle.

Effect of altitude. - The variation of net thrust and specific fuel consumption with altitude for the constant- and variable-area exhaust nozzles with an assumed efficiency of 100 percent (fig. 9) was obtained from cross plots of curves similar to those shown in figure 6. Because the turbine-outlet temperature increased as the altitude was raised at a given flight Mach number, it was necessary to reduce the rotational speed as the altitude was increased in order to operate within the temperature limits with the constant-area nozzle. With the variable-area nozzle, however, rated speed and limiting turbine-outlet temperatures were maintained at high altitudes by increasing the nozzle area.

At an altitude of 15,000 feet and a flight Mach number of 0.53, a turbine-outlet temperature of about 1600° R was obtained at an engine speed of 12,500 rpm with the constant-area exhaust nozzle; whereas at 45,000 feet and the same flight Mach number, the limiting turbine-outlet temperature (1600° R) was obtained at 11,150 rpm. For altitudes from 15,000 to 25,000 feet, the net thrust and the specific fuel consumption obtained with both exhaust nozzles operating at 100-percent efficiency were approximately the same. The slight disagreement at low altitudes is attributed to experimental inaccuracies in the data. At altitudes above approximately 30,000 feet, however, at which the engine speed with the constant-area nozzle was considerably reduced, higher thrusts and slightly lower specific fuel consumptions were obtained with the variable-area nozzle (fig. 9).

Performance with Actual Exhaust-Nozzle Efficiencies

Performance data obtained with the exhaust-nozzle efficiencies indicated in figure 5 are shown in figure 10 for the variable- and constant-area nozzles at several flight conditions. With the efficiencies shown in figure 5, higher thrusts and lower specific fuel consumptions were more often obtained with the constant-area nozzle than with the variable-area nozzle (fig. 10).

Exhaust-nozzle efficiencies and the effect they can produce on net thrust and specific fuel consumption are shown in figure 11 for an altitude of 25,000 feet and a flight Mach number of 0.53. An efficiency of about 95 percent is indicated for the constant-area nozzle, whereas an efficiency of about 91 percent is shown for the variable-area nozzle at rated engine speed. The nozzle losses have a larger percentage effect on net thrust and specific fuel consumption based on net thrust than they do on the nozzle efficiency, which is based on jet thrust. For nozzle efficiencies of 100 percent, the net thrust with the constant-area nozzle was 2 percent higher than with the variable-area nozzle at 1600° R. For the actual nozzle efficiencies, the net thrust with the constant-area nozzle was about 8 percent higher than with the variable-area nozzle at 1600° R. At a net thrust of 1200 pounds, the specific fuel consumptions with both nozzles were about the same for nozzle efficiencies of 100 percent. With the actual nozzle efficiencies at the same thrust, however, the specific fuel consumption with the variable-area nozzle was 8 percent higher than with the constant-area nozzle.

Effect of flight Mach number. - From a cross plot of curves similar to those shown in figure 10, the variation of measured net thrust and specific fuel consumption with flight Mach number was obtained (fig. 12). For all flight Mach numbers investigated at an altitude of 25,000 feet, higher thrusts and lower specific fuel consumptions were obtained with the constant-area nozzle than with the variable-area nozzle. The relatively low thrust and high specific fuel consumption obtained with the variable-area nozzle is a direct effect of the nozzle losses. The variation of specific fuel consumption with flight Mach number for both types of nozzle is shown in figure 13 for three reduced values of net thrust. Thrust with the variable-area nozzle was reduced by increasing the nozzle area. Although most of the data with this nozzle are for rated engine speed, in a few cases an engine speed of 12,000 rpm was used because a slightly lower specific fuel consumption was obtainable at the same thrust. For practically all flight Mach numbers at the three thrust values shown, the specific fuel consumption obtained with the constant-area nozzle was lower than that obtained with the variable-area nozzle.

An advantage of the variable-area exhaust nozzle is the degree of thrust variation that can be obtained without changing the rotational speed of the engine. The variation of net thrust with exhaust-nozzle area for various flight Mach numbers at 25,000 feet is presented in figure 14. For the range of data investigated, the percentage decrease in thrust that was obtained for a given increase in nozzle area is independent of flight Mach number. The data shown for flight Mach numbers of 0.12 and 0.25 indicate that little change in thrust can be obtained by further increases in nozzle area.

Effect of altitude. - The variation of net thrust and specific fuel consumption with altitude (fig. 15) was obtained from cross plots of curves similar to those shown in figure 10. For altitudes from 15,000 to 25,000 feet, the thrust obtained with the constant-area nozzle was considerably higher than that obtained with the variable-area nozzle. As the altitude was increased, however, the engine speed with the constant-area nozzle was reduced in order to stay within the engine temperature limits. Thus at altitudes above 37,000 feet, a higher thrust was obtained with the variable-area nozzle than with the constant-area nozzle (fig. 15). The specific fuel consumption at all altitudes investigated was higher with the variable-area nozzle than with the constant-area nozzle.

The variation of net thrust with exhaust-nozzle area for various altitudes at a flight Mach number of approximately 0.53 is presented in figure 16. For a given increase in nozzle area, the decrease in thrust that was obtained was essentially independent of altitude.

SUMMARY OF RESULTS

The following results were obtained from an altitude-wind-tunnel investigation of turbojet engine performance with constant- and variable-area exhaust nozzles for a wide range of altitudes and flight Mach numbers. The engine has an 11-stage axial-flow compressor and a two-stage turbine.

1. The efficiency of the variable-area exhaust nozzle was 1.5 to 8 percent lower than that of the constant-area nozzle. As a result, the net thrust with the variable-area nozzle at an altitude of 25,000 feet, a flight Mach number of 0.53, and a turbine-outlet temperature of 1600° R was 8 percent lower than that obtained with the constant-area nozzle. At the same flight conditions and a net thrust of 1200 pounds, the specific fuel consumption was 8 percent higher with the variable-area nozzle than with the constant-area nozzle.

2. With the results corrected to a nozzle efficiency of 100 percent, approximately the same net thrust and specific fuel consumption was obtained at limiting engine conditions for the variable- and constant-area nozzles. Reducing the thrust by decreasing the engine speed with the constant-area nozzle or by increasing the nozzle area with the variable-area nozzle resulted in about the same specific fuel consumption.

3. At an altitude of 25,000 feet and a flight Mach number of 0.53, increasing the nozzle area 33 percent decreased the thrust about 46 percent. An equal thrust reduction with the constant-area nozzle required an estimated reduction in engine speed from 12,350 to about 10,500 rpm.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

APPENDIX

METHODS OF CALCULATION

Symbols

A	cross-sectional area, sq ft
F_j	jet thrust, lb
F_j'	jet thrust assuming no losses in tail pipe or nozzle, lb
F_n	net thrust, lb
F_n'	net thrust assuming no losses in tail pipe or nozzle, lb
g	acceleration due to gravity, 32.2 ft/sec^2
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	gas constant, 53.3 ft-lb/(lb)(^{o}R)
T	total temperature, ^{o}R
T_i	indicated temperature, ^{o}R
t	static temperature, ^{o}R
V	velocity, ft/sec
W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
W_g	gas flow, lb/sec
W_f/F_n	net thrust specific fuel consumption, lb/(hr)(lb thrust)
α	thermocouple recovery factor, 0.85
γ	ratio of specific heats
η	exhaust-nozzle efficiency, ratio of measured jet thrust to jet thrust obtainable with no tail-pipe or nozzle losses

Subscripts:

0 free-stream conditions

2 compressor inlet

5 turbine outlet

Temperature

Total temperature was calculated from

$$T = \frac{T_i\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}}}{1 + \alpha\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{1}$$

Air Flow

The engine air flow was obtained from

$$W_a = p_2 A_2 \sqrt{\frac{2\gamma g}{(\gamma-1)RT_2}\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}}\left[\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{2}$$

Net Thrust

The free-stream momentum of the engine air flow was subtracted from the jet thrust, as measured by the tunnel balance scales, to obtain the net thrust

$$F_n = F_j - \frac{W_a V_0}{g}$$

The ideal jet thrust that was required to determine the exhaust-nozzle efficiency was obtained from the engine mass flow, measurements at the turbine outlet, and the ambient static pressure

$$F_j' = \frac{W_g}{g}\sqrt{\frac{2\gamma}{\gamma-1} Rg\, T_5\left[1 - \left(\frac{p_0}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{3}$$

The exhaust-nozzle efficiency was defined as 912

$$\eta = \frac{F_j}{F_j'}$$

TABLE I - PERFORMANCE DATA FOR TURBOJET

	1	2	3	4	5	6	7	8	9	10
Run	Altitude, (ft)	Ambient pressure, p_0 (lb/sq ft abs.)	Ambient temperature t_0, (°R)	Flight Mach number	Engine speed, (rpm)	Projected exhaust-nozzle area, (sq ft)	Fuel flow, W_f (lb/hr)	Air flow, W_a (lb/sec)	Measured jet thrust F_j, (lb)	Net thrust, F_n (lb)
1	5,000	1753	499	0.11	11,000	1.811	1119	44.77	1071	835
2	5,000	1760	497	.12	11,000	1.447	1453	44.60	1500	1258
3	5,000	1753	498	.11	11,000	1.312	1705	44.65	1711	1481
4	5,000	1753	497	.13	11,000	1.178	2101	44.24	2046	1799
5	5,000	1753	498	.12	11,000	1.134	2325	43.90	2170	1931
6	5,000	1753	514	.12	12,000	1.762	1394	47.45	1375	1113
7	5,000	1753	508	.11	12,000	1.403	1861	48.17	1899	1648
8	5,000	1753	506	.11	12,000	1.255	2264	48.23	2252	1996
9	5,000	1760	506	.13	12,000	1.190	2660	48.54	2539	2258
10	5,000	1760	493	.12	12,500	1.881	1549	50.84	1514	1239
11	5,000	1753	497	.13	12,500	1.443	2000	51.00	2071	1778
12	5,000	1753	515	.13	12,500	1.332	2192	49.31	2214	1934
13	5,000	1753	508	.13	12,500	1.240	2660	49.78	2558	2277
14	15,000	1184	468	.53	11,000	1.363	1129	36.76	1438	795
15	15,000	1189	974	.53	11,000	1.213	1404	35.91	1666	1044
16	15,000	1189	464	.53	11,000	1.129	1784	36.44	1925	1296
17	15,000	1186	466	.53	11,000	1.085	1940	35.99	1993	1366
18	15,000	1184	465	.53	11,000	1.042	2049	36.28	2073	1443
19	15,000	1188	466	.52	12,000	1.564	1149	39.99	1462	779
20	15,000	1188	467	.53	12,000	1.296	1617	39.91	1933	1244
21	15,000	1190	467	.52	12,000	1.219	1871	39.62	2103	1426
22	15,000	1190	465	.53	12,000	1.149	2212	40.21	2341	1651
23	15,000	1188	466	.53	12,500	1.724	1208	41.30	1481	763
24	15,000	1189	466	.53	12,500	1.367	1656	41.38	1984	1259
25	15,000	1190	466	.55	12,500	1.257	1960	41.38	2228	1503
26	15,000	1190	464	.53	12,500	1.197	2284	41.49	2445	1725
27	25,000	774	453	.12	11,000	1.543	709	21.94	698	588
28	25,000	781	453	.13	11,000	1.259	981	22.11	973	855
29	25,000	774	453	.11	11,000	1.209	1026	21.72	999	892
30	25,000	781	453	.13	11,000	1.127	1252	21.73	1130	1014
31	25,000	774	453	.12	12,000	1.662	788	23.70	780	657
32	25,000	774	454	.13	12,000	1.337	1070	23.57	1088	962
33	25,000	774	453	.12	12,000	1.251	1241	23.50	1209	1087
34	25,000	781	453	.14	12,000	1.209	1373	24.01	1346	1209
35	25,000	781	455	.13	12,500	1.881	809	23.95	725	597
36	25,000	781	453	.13	12,500	1.441	1031	24.01	1007	879
37	25,000	774	452	.14	12,500	1.310	1231	23.96	1183	1046
38	25,000	788	452	.14	12,500	1.258	1404	24.43	1310	1171
39	25,000	774	449	.25	11,000	1.426	778	22.37	811	625
40	25,000	781	448	.26	11,000	1.265	981	22.74	1022	824
41	25,000	774	448	.25	11,000	1.200	1075	22.30	1076	895
42	25,000	781	449	.25	11,000	1.126	1277	22.25	1192	1009
43	25,000	781	449	.25	12,000	1.657	793	24.33	825	623
44	25,000	781	449	.25	12,000	1.343	1050	24.23	1098	897
45	25,000	781	449	.25	12,000	1.257	1236	24.21	1236	1037
46	25,000	781	448	.25	12,000	1.211	1358	24.14	1326	1130
47	25,000	774	449	.26	12,500	1.881	809	24.48	760	555
48	25,000	774	448	.26	12,500	1.387	1094	24.45	1100	893
49	25,000	774	449	.26	12,500	1.291	1277	24.51	1243	1033
50	25,000	781	449	.25	12,500	1.253	1424	24.69	1367	1162
51	25,000	781	431	.53	11,000	1.341	899	26.35	1105	660
52	25,000	778	431	.53	11,000	1.230	1055	26.26	1244	802
53	25,000	777	433	.53	11,000	1.142	1236	25.83	1356	922
54	25,000	778	433	.53	11,000	1.091	1444	25.43	1472	1047
55	25,000	781	431	.53	12,000	1.487	930	28.26	1132	662
56	25,000	781	431	.53	12,000	1.282	1201	28.26	1402	932
57	25,000	778	431	.53	12,000	1.213	1409	28.26	1563	1087
58	25,000	781	431	.53	12,000	1.149	1615	28.18	1684	1213
59	25,000	781	431	.53	12,500	1.610	945	28.60	1100	662
60	25,000	781	430	.53	12,500	1.358	1216	28.60	1383	904
61	25,000	781	431	.53	12,500	1.255	1488	28.71	1601	1120

[a]Data adjusted for altitude temperature variations..

ENGINE WITH VARIABLE-AREA EXHAUST NOZZLE

11	12	13	14	15	16	17	18	19	20	
Specific fuel consumption, W_f/F_n, (lb/(hr)(lb thrust))	Turbine-outlet temperature, T_5, (°R)	Calculated jet thrust, F_j', (lb)	Net thrust, F_n' (lb)	Specific fuel consumption, W_f/F_n' (lb/(hr)(lb thrust))	Exhaust-nozzle efficiency, η	Corrected engine speed, N, (rpm)[a]	Corrected specific fuel consumption, W_f/F_n (lb/(hr)(lb thrust))[a]	Corrected turbine-outlet temperature T_5, (°R)[a]	Corrected specific fuel consumption, W_f/F_n' (lb/(hr)(lb thrust))[a]	Run
1.340	1029	1165	929	1.205	0.919	11,020	1.342	1032	1.209	1
1.155	1184	1592	1350	1.076	.942	11,040	1.160	1193	1.079	2
1.151	1300	1868	1638	1.041	.916	11,031	1.155	1307	1.044	3
1.168	1481	2205	1958	1.073	.928	11,040	1.174	1492	1.076	4
1.204	1571	2352	2113	1.100	.923	11,030	1.208	1580	1.103	5
1.252	1139	1514	1252	1.113	.908	11,840	1.247	1110	1.098	6
1.129	1313	2063	1812	1.027	.921	11,910	1.121	1295	1.022	7
1.134	1478	2437	2181	1.038	.924	11,940	1.129	1462	1.033	8
1.178	1627	2758	2477	1.074	.921	11,940	1.174	1608	1.069	9
1.250	1138	1691	1416	1.094	.895	12,590	1.261	1153	1.101	10
1.125	1319	2235	1942	1.030	.927	12,550	1.129	1328	1.033	11
1.133	1450	2392	2112	1.038	.926	12,330	1.118	1410	1.024	12
1.168	1619	2793	2512	1.059	.916	12,410	1.161	1594	1.054	13
1.420	1138	1582	939	1.202	.909	10,960	1.416	1131	1.200	14
1.345	1317	1776	1154	1.217	.938	10,890	1.333	1289	1.205	15
1.377	1496	2110	1481	1.205	.912	11,010	1.379	1500	1.207	16
1.420	1594	2214	1587	1.222	.900	10,990	1.419	1590	1.221	17
1.420	1530	2233	1603	1.278	.928	11,000	1.419	1528	1.277	18
1.475	1110	1577	894	1.285	.927	11,990	1.474	1108	1.284	19
1.300	1336	2072	1383	1.169	.933	11,970	1.297	1332	1.166	20
1.312	1461	2263	1586	1.180	.929	11,970	1.310	1455	1.178	21
1.340	1635	2587	1897	1.166	.905	12,000	1.340	1632	1.165	22
1.583	1121	1629	911	1.326	.909	12,480	1.581	1119	1.326	23
1.315	1325	2127	1402	1.181	.933	12,480	1.314	1322	1.180	24
1.304	1468	2392	1667	1.176	.931	12,480	1.304	1463	1.176	25
1.324	1634	2666	1946	1.174	.917	12,515	1.326	1640	1.176	26
1.206	1083	747	637	1.113	.934	10,710	1.175	1028	1.084	27
1.147	1363	1045	927	1.058	.931	10,710	1.119	1292	1.031	28
1.150	1421	1105	998	1.028	.904	10,710	1.121	1348	1.001	29
1.235	1629	1280	1164	1.076	.883	10,710	1.204	1542	1.049	30
1.199	1117	852	729	1.081	.916	11,690	1.169	1058	1.054	31
1.112	1387	1171	1045	1.024	.929	11,660	1.082	1309	.995	32
1.142	1538	1319	1197	1.037	.917	11,690	1.113	1458	1.011	33
1.136	1646	1469	1332	1.031	.916	11,690	1.107	1560	1.005	34
1.355	1127	832	704	1.149	.871	12,140	1.317	1062	1.116	35
1.173	1337	1112	984	1.048	.906	12,170	1.143	1267	1.021	36
1.177	1522	1306	1169	1.053	.906	12,170	1.147	1442	1.026	37
1.199	1634	1448	1309	1.073	.905	12,170	1.169	1549	1.046	38
1.245	1137	871	685	1.136	.931	10,750	1.217	1087	1.111	39
1.191	1331	1100	902	1.088	.929	10,760	1.166	1273	1.064	40
1.201	1431	1166	985	1.091	.923	10,760	1.176	1370	1.067	41
1.266	1632	1336	1153	1.108	.892	10,750	1.239	1560	1.083	42
1.273	1103	889	687	1.154	.928	11,730	1.245	1053	1.128	43
1.171	1328	1179	978	1.074	.931	11,730	1.144	1268	1.050	44
1.192	1492	1344	1145	1.079	.920	11,730	1.166	1426	1.055	45
1.202	1602	1442	1246	1.090	.920	11,750	1.177	1533	1.067	46
1.458	1112	865	660	1.226	.879	12,220	1.427	1062	1.198	47
1.225	1362	1196	989	1.106	.920	12,240	1.199	1303	1.082	48
1.236	1526	1375	1165	1.096	.904	12,220	1.209	1458	1.071	49
1.225	1629	1491	1286	1.107	.917	12,220	1.199	1557	1.082	50
1.362	1150	1198	753	1.194	.922	10,980	1.359	1144	1.190	51
1.315	1285	1361	919	1.148	.914	10,980	1.313	1279	1.144	52
1.341	1436	1499	1065	1.161	.905	10,950	1.336	1423	1.156	53
1.379	1625	1652	1227	1.177	.891	10,950	1.374	1612	1.172	54
1.405	1122	1234	764	1.217	.917	11,970	1.404	1117	1.213	55
1.289	1324	1526	1056	1.137	.919	11,970	1.286	1319	1.133	56
1.296	1493	1781	1305	1.080	.878	11,970	1.294	1487	1.076	57
1.331	1640	1871	1400	1.154	.900	11,970	1.329	1631	1.150	58
1.519	1127	1216	738	1.280	.905	12,480	1.516	1120	1.276	59
1.345	1334	1521	1042	1.167	.909	12,490	1.345	1334	1.167	60
1.329	1530	1766	1285	1.158	.907	12,480	1.326	1522	1.154	61

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TABLE I - PERFORMANCE DATA FOR TURBOJET ENGINE

	1	2	3	4	5	6	7	8	9	10
Run	Altitude, (ft)	Ambient pressure, P_0 (lb/sq ft abs.)	Ambient temperature, t_0, (°R)	Flight Mach number	Engine speed, (rpm)	Projected exhaust-nozzle area, (sq ft)	Fuel flow, W_f (lb/hr)	Air flow, W_a (lb/sec)	Measured jet thrust F_j, (lb)	Net thrust, F_n (lb)
62	25,000	(b)	427	0.55	12,500	1.211	1640	27.34	1699	1221
63	25,000	778	425	.72	11,000	1.269	930	29.68	1315	639
64	25,000	778	423	.73	11,000	1.183	1221	29.83	1571	889
65	25,000	778	429	.73	11,000	1.096	1394	29.48	1673	989
66	25,000	778	427	.73	11,000	1.026	1650	29.18	1797	1126
67	25,000	778	426	.73	12,000	1.455	991	32.21	1432	692
68	25,000	781	428	.73	12,000	1.255	1333	32.30	1743	1000
69	25,000	778	427	.73	12,000	1.195	1582	32.17	1913	1173
70	25,000	778	427	.73	12,000	1.139	1800	32.09	2035	1299
71	25,000	781	428	.73	12,500	1.530	1031	32.78	1432	681
72	25,000	778	427	.73	12,500	1.325	1333	32.72	1735	986
73	25,000	781	428	.72	12,500	1.247	1572	32.85	1920	1170
74	25,000	778	426	.73	12,500	1.195	1815	32.86	2098	1344
75	25,000	781	429	.86	11,000	1.282	957	32.48	1527	641
76	25,000	781	429	.86	11,000	1.147	1297	32.64	1789	896
77	25,000	784	426	.86	11,000	1.103	1511	32.35	1895	1013
78	25,000	781	426	.86	11,000	1.026	1695	31.91	2009	1142
79	25,000	781	430	.86	12,000	1.465	1007	35.48	1615	643
80	25,000	781	430	.86	12,000	1.255	1394	35.55	1982	1011
81	25,000	781	429	.87	12,000	1.158	1724	35.74	2221	1241
82	25,000	781	428	.87	12,000	1.122	1970	35.72	2343	1362
83	25,000	778	430	.86	12,500	1.486	1119	36.61	1732	727
84	25,000	781	431	.86	12,500	1.264	1503	36.33	2081	1087
85	25,000	778	431	.87	12,500	1.228	1735	36.41	2254	1254
86	25,000	778	429	.86	12,500	1.190	1998	36.30	2407	1413
87	25,000	781	393	.94	11,000	1.356	977	37.68	1710	633
88	25,000	781	393	.94	11,000	1.195	1375	38.54	2089	986
89	25,000	781	389	.95	11,000	1.113	1666	35.96	2214	1181
90	25,000	781	390	.95	11,000	1.026	2000	38.96	2485	1371
91	25,000	781	394	.95	12,000	1.443	1179	41.22	2016	826
92	25,000	796	395	.94	12,000	1.267	1520	41.03	2331	1160
93	25,000	810	397	.93	12,000	1.165	1940	41.64	2611	1437
94	25,000	803	395	.93	12,000	1.096	2325	40.59	2781	1636
95	25,000	803	399	.94	12,500	1.518	1239	42.29	2040	829
96	25,000	810	400	.93	12,500	1.304	1675	42.37	2450	1243
97	25,000	817	399	.93	12,500	1.207	2050	42.62	2737	1533
98	25,000	896	398	.93	12,500	1.147	2356	42.28	2888	1686
99	35,000	493	431	.52	11,000	1.378	603	16.53	667	396
100	35,000	500	432	.51	11,000	1.253	734	16.47	793	528
101	35,000	493	431	.52	11,000	1.163	854	16.14	861	596
102	35,000	493	431	.53	11,000	1.119	935	16.08	906	637
103	35,000	493	431	.53	12,000	1.577	613	17.89	692	391
104	35,000	500	430	.53	12,000	1.319	809	18.03	899	600
105	35,000	500	432	.53	12,000	1.255	925	17.90	987	689
106	35,000	500	433	.51	12,000	1.207	1031	17.67	1042	760
107	35,000	493	435	.52	12,500	1.881	598	17.68	588	298
108	35,000	486	429	.55	12,500	1.407	768	17.87	860	551
109	35,000	493	432	.53	12,500	1.309	905	17.98	956	655
110	35,000	500	432	.51	12,500	1.251	1036	18.01	1049	757
111	45,000	303	432	.51	11,000	1.547	370	9.82	361	202
112	45,000	303	433	.52	11,000	1.337	481	9.84	477	315
113	45,000	310	430	.52	11,000	1.264	527	9.82	511	351
114	45,000	303	431	.53	11,000	1.187	613	9.73	559	397
115	45,000	303	437	.52	12,000	1.734	410	10.62	402	226
116	45,000	303	433	.51	12,000	1.403	537	10.60	550	380
117	45,000	303	432	.53	12,000	1.325	593	10.80	595	416
118	45,000	303	431	.53	12,000	1.264	663	11.39	668	478
119	45,000	303	431	.51	12,500	1.881	446	10.62	414	242
120	45,000	303	430	.52	12,500	1.486	532	10.90	535	356
121	45,000	303	430	.52	12,500	1.403	618	10.86	619	442
122	45,000	303	431	.52	12,500	1.349	653	10.64	631	456

[a]Data adjusted for altitude temperature variations.
[b]Data not obtained.

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WITH VARIABLE-AREA EXHAUST NOZZLE - Concluded

11	12	13	14	15	16	17	18	19	20	
Specific fuel consumption, W_f/F_n, (lb/(hr)(lb thrust))	Turbine-outlet temperature, T_5, (°R)	Calculated jet thrust, F_j', (lb)	Net thrust, F_n' (lb)	Specified fuel consumption, W_f/F_n' (lb/(hr)(lb thrust))	Exhaust-nozzle efficiency, η	Corrected engine speed, N, (rpm)[a]	Corrected specific fuel consumption, W_f/F_n (lb/(hr)(lb thrust))[a]	Corrected turbine-outlet temperature T_5, (°R)[a]	Corrected specific fuel consumption, W_f/F_n' (lb/(hr)(lb thrust))[a]	Run
1.343	1638	1886	1378	1.190	0.915	12,530	1.346	1645	1.193	62
1.455	1115	1419	743	1.252	.927	11,050	1.463	1125	1.257	63
1.373	1312	1717	1035	1.180	.915	11,080	1.385	1332	1.189	64
1.410	1469	1869	1185	1.176	.895	11,000	1.411	1419	1.176	65
1.465	1634	2037	1366	1.208	.882	11,020	1.469	1641	1.211	66
1.432	1110	1535	795	1.247	.933	12,040	1.439	1119	1.252	67
1.333	1324	1884	1141	1.168	.925	12,010	1.336	1328	1.168	68
1.349	1492	2100	1360	1.163	.911	12,020	1.352	1500	1.165	69
1.386	1636	2268	1532	1.175	.897	12,020	1.390	1642	1.178	70
1.514	1127	1557	806	1.279	.920	12,510	1.517	1128	1.279	71
1.352	1313	1873	1124	1.186	.926	12,520	1.356	1319	1.189	72
1.344	1470	2095	1345	1.169	.916	12,510	1.346	1408	1.169	73
1.350	1623	2290	1536	1.182	.916	12,550	1.357	1571	1.187	74
1.493	1107	1627	741	1.291	.939	11,000	1.494	1107	1.291	75
1.448	1328	1971	1078	1.203	.908	11,000	1.449	1328	1.203	76
1.492	1454	2123	1241	1.218	.893	11,040	1.499	1468	1.223	77
1.484	1595	2271	1404	1.207	.885	11,040	1.490	1608	1.212	78
1.566	1101	1751	779	1.293	.922	11,990	1.566	1101	1.293	79
1.379	1321	2155	1184	1.177	.920	11,990	1.379	1321	1.177	80
1.389	1495	2441	1461	1.180	.910	12,000	1.390	1495	1.180	81
1.446	1648	2648	1667	1.182	.885	12,010	1.449	1650	1.182	82
1.539	1146	1898	893	1.253	.913	12,490	1.540	1146	1.253	83
1.383	1360	2268	1274	1.180	.918	12,470	1.380	1352	1.176	84
1.384	1493	2480	1480	1.172	.909	12,470	1.381	1488	1.168	85
1.414	1616	2644	1650	1.211	.910	12,500	1.416	1616	1.212	86
1.543	1005	1868	791	1.235	.915	11,490	1.613	1097	1.289	87
1.395	1231	2341	1238	1.111	.892	11,490	1.458	1343	1.160	88
1.411	1357	2397	1364	1.221	.924	11,550	1.483	1497	1.281	89
1.459	1558	2900	1786	1.120	.851	11,540	1.531	1718	1.176	90
1.427	1082	2187	997	1.185	.922	12,530	1.491	1182	1.234	91
1.310	1253	2527	1356	1.121	.922	12,510	1.377	1361	1.167	92
1.350	1444	2896	1724	1.125	.901	12,480	1.404	1560	1.168	93
1.421	1625	3122	1977	1.176	.891	12,510	1.482	1763	1.225	94
1.495	1106	2241	1030	1.203	.910	12,970	1.553	1188	1.249	95
1.348	1307	2679	1472	1.138	.915	12,940	1.397	1403	1.179	96
1.337	1496	3021	1817	1.128	.906	12,970	1.389	1608	1.171	97
1.397	1630	3237	2035	1.158	.892	12,970	1.453	1760	1.202	98
1.523	1142	732	461	1.308	.911	10,510	1.455	1041	1.250	99
1.390	1328	865	600	1.223	.917	10,505	1.327	1207	1.169	100
1.433	1495	966	701	1.218	.891	10,510	1.370	1362	1.164	101
1.468	1647	1043	774	1.208	.869	10,510	1.402	1500	1.154	102
1.568	1109	753	452	1.356	.919	11,460	1.499	1010	1.296	103
1.348	1360	983	684	1.183	.915	11,480	1.292	1247	1.134	104
1.343	1495	1079	781	1.184	.915	11,460	1.281	1361	1.131	105
1.357	1638	1154	872	1.182	.903	11,440	1.295	1488	1.130	106
2.007	1108	697	407	1.469	.844	11,890	1.910	1001	1.398	107
1.394	1333	933	624	1.231	.922	11,970	1.336	1222	1.179	108
1.382	1494	1059	758	1.194	.903	11,930	1.319	1361	1.141	109
1.369	1624	1159	867	1.195	.905	11,930	1.307	1479	1.142	110
1.832	1113	395	236	1.568	.914	10,490	1.744	1010	1.494	111
1.527	1350	512	350	1.374	.932	10,480	1.455	1223	1.309	112
1.501	1450	545	385	1.369	.938	10,510	1.435	1328	1.309	113
1.544	1634	616	454	1.350	.908	10,500	1.473	1488	1.286	114
1.814	1164	449	273	1.502	.895	11,380	1.720	1047	1.424	115
1.413	1422	578	408	1.316	.952	11,440	1.346	1290	1.254	116
1.425	1525	643	464	1.278	.925	11,440	1.359	1382	1.218	117
1.387	1675	747	557	1.190	.894	11,450	1.324	1522	1.134	118
1.843	1198	465	293	1.522	.890	11,940	1.759	1089	1.451	119
1.494	1428	589	410	1.298	.908	11,940	1.429	1307	1.241	120
1.398	1578	658	481	1.285	.941	11,940	1.337	1443	1.229	121
1.432	1616	667	492	1.327	.946	11,940	1.366	1469	1.265	122

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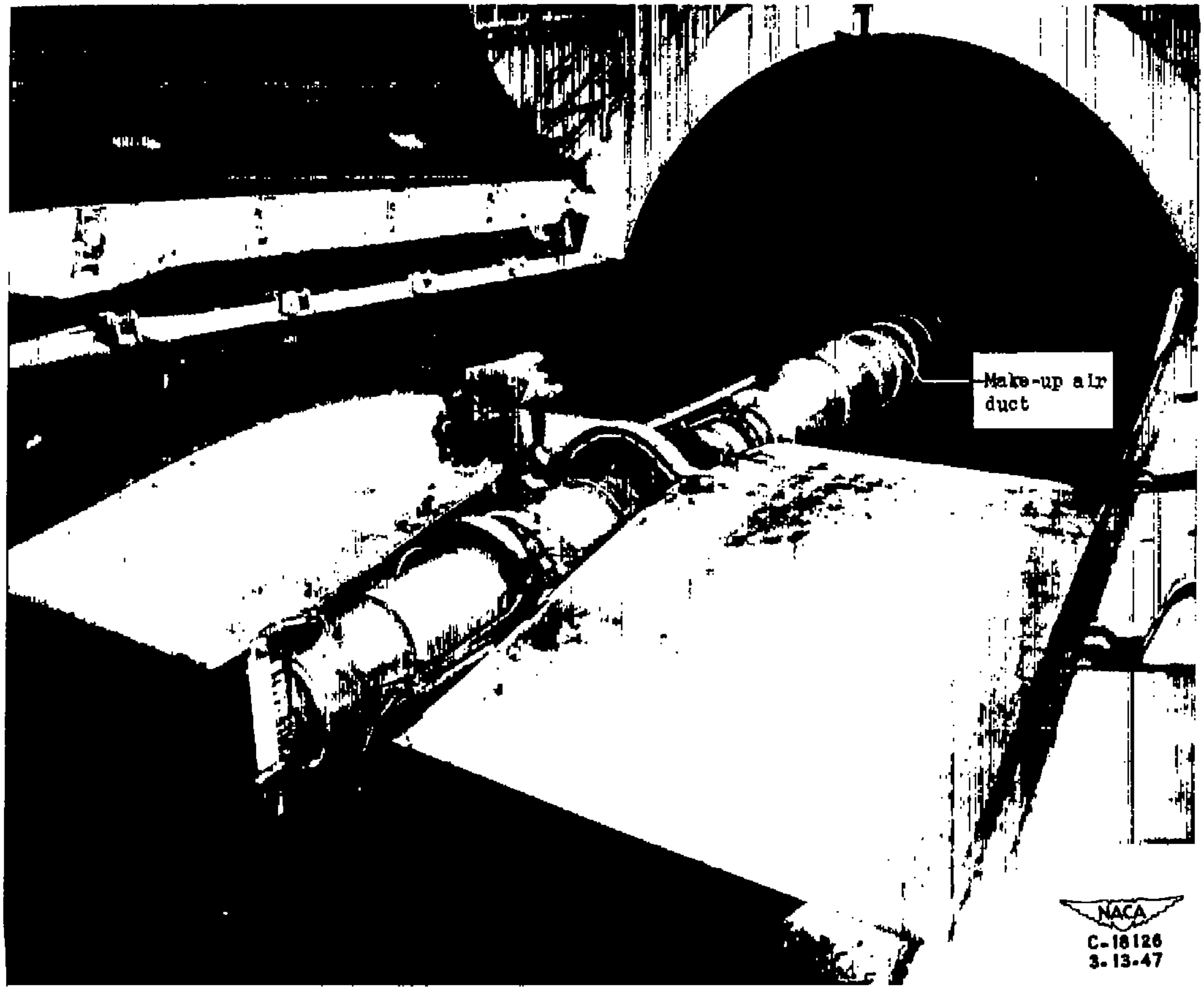

Figure 1. - Installation of turbojet engine in altitude wind tunnel.

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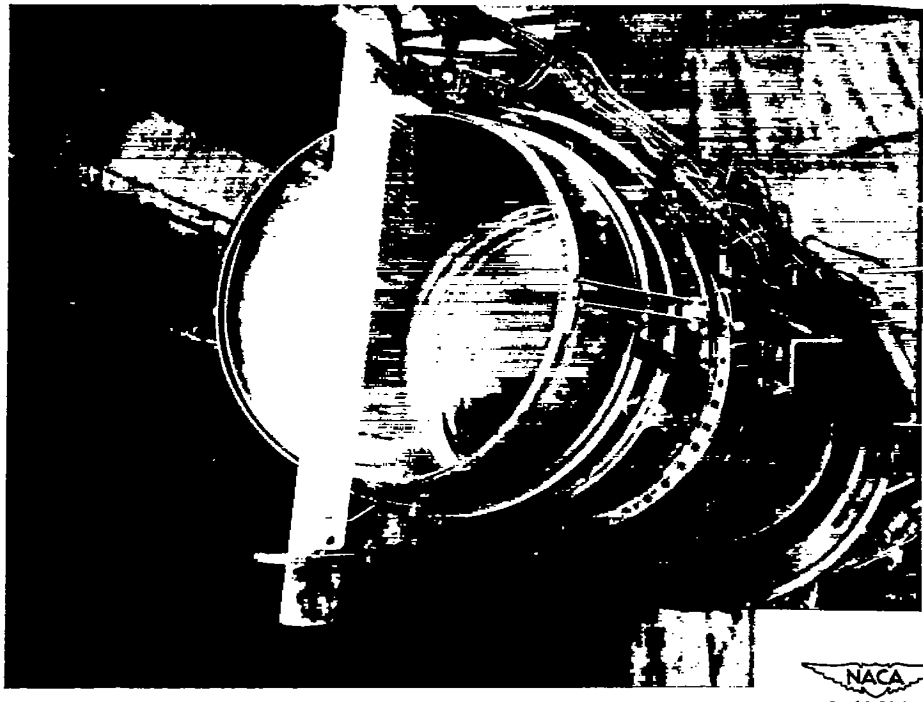
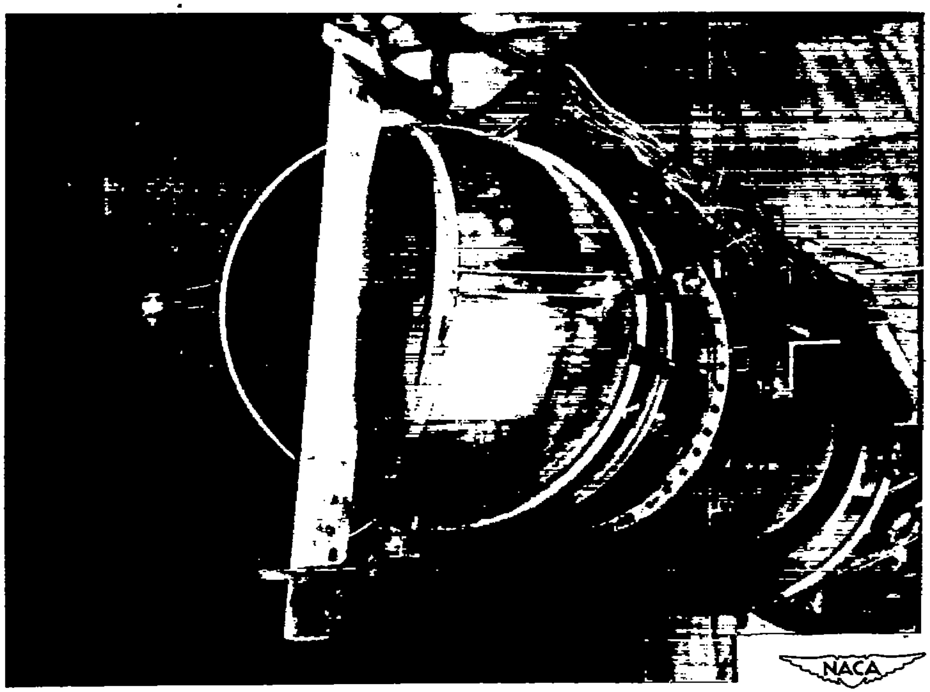


C-18693
5-12-47

(a) Nozzle in open position.



C-18692
5-12-47

(b) Nozzle in closed position.

Figure 2. - Tail pipe of turbojet engine with variable-area exhaust nozzle.

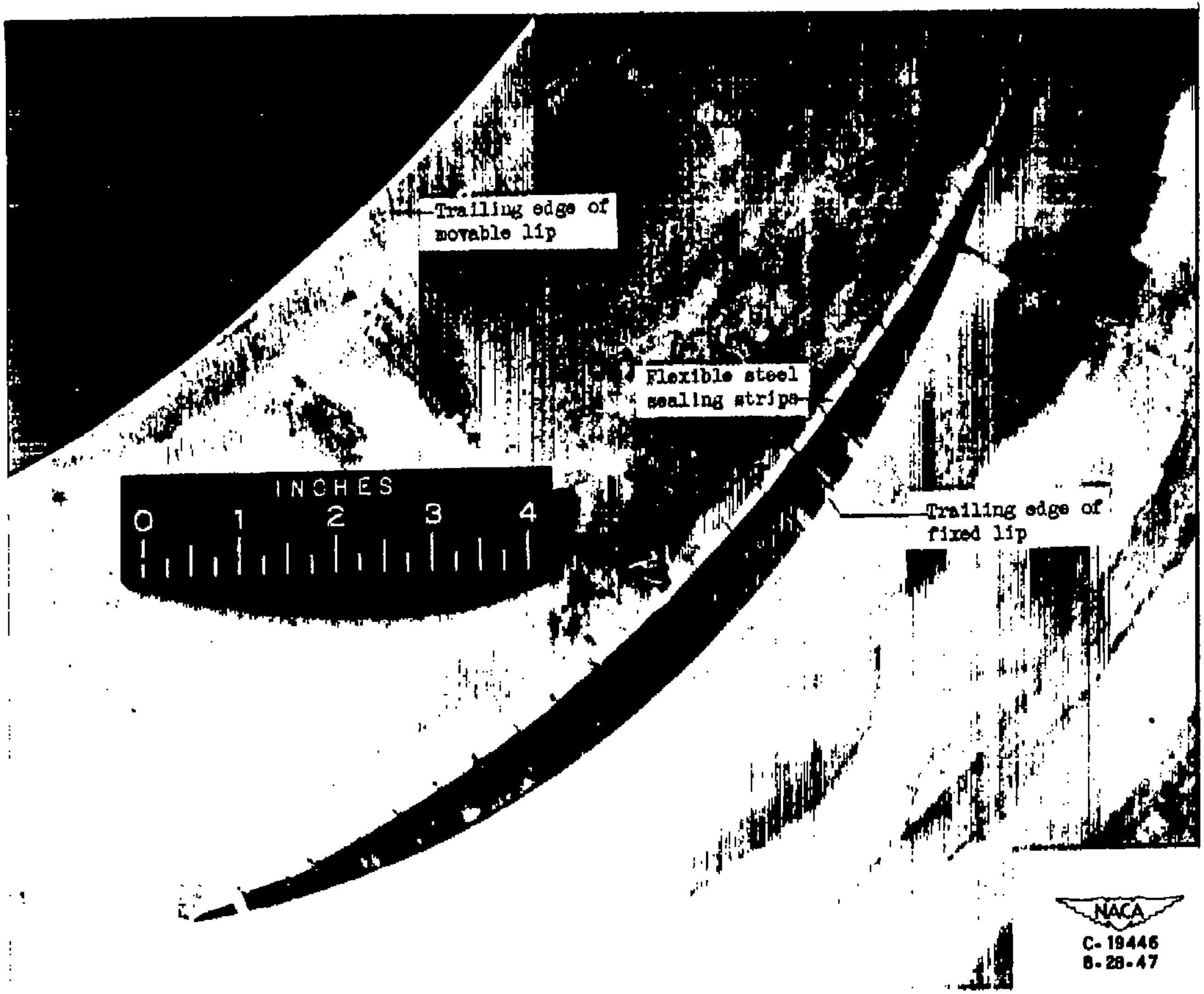


Figure 3. - Variable-area exhaust nozzle with flexible sealing lip between tail pipe and nozzle viewed from inside of pipe looking downstream.

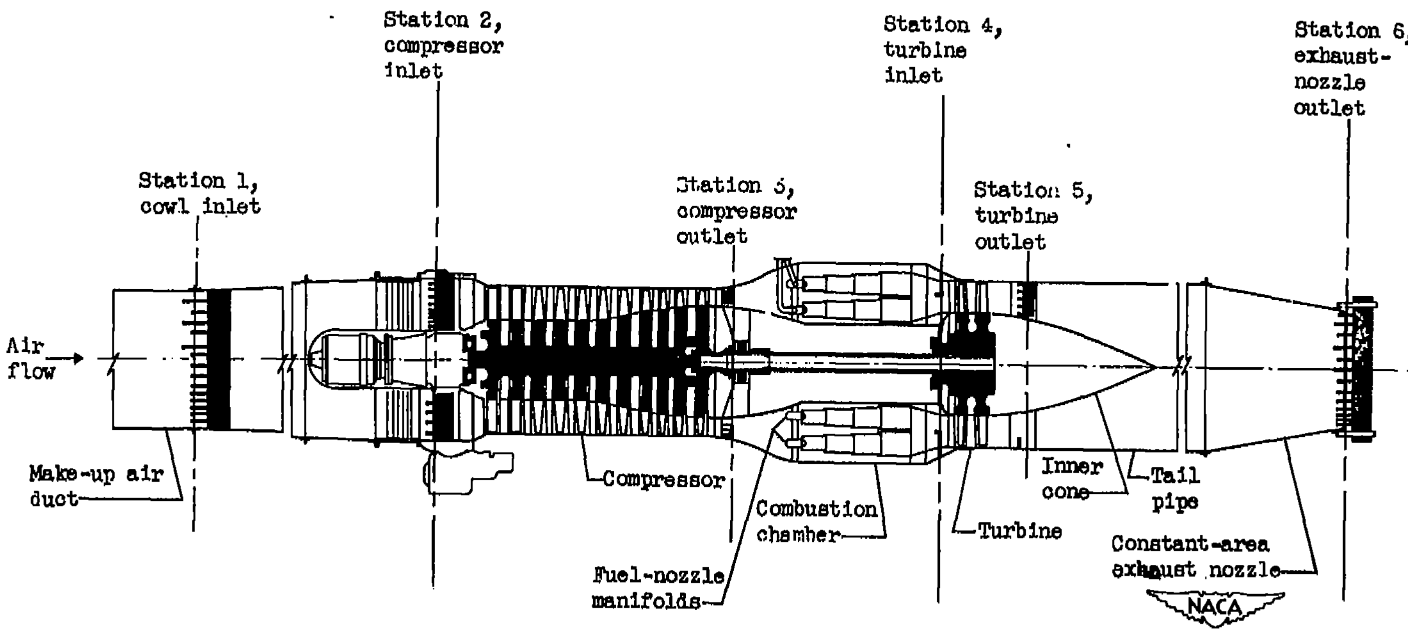


Figure 4. - Cross section of turbojet installation showing relation of component parts and measuring stations in engine.

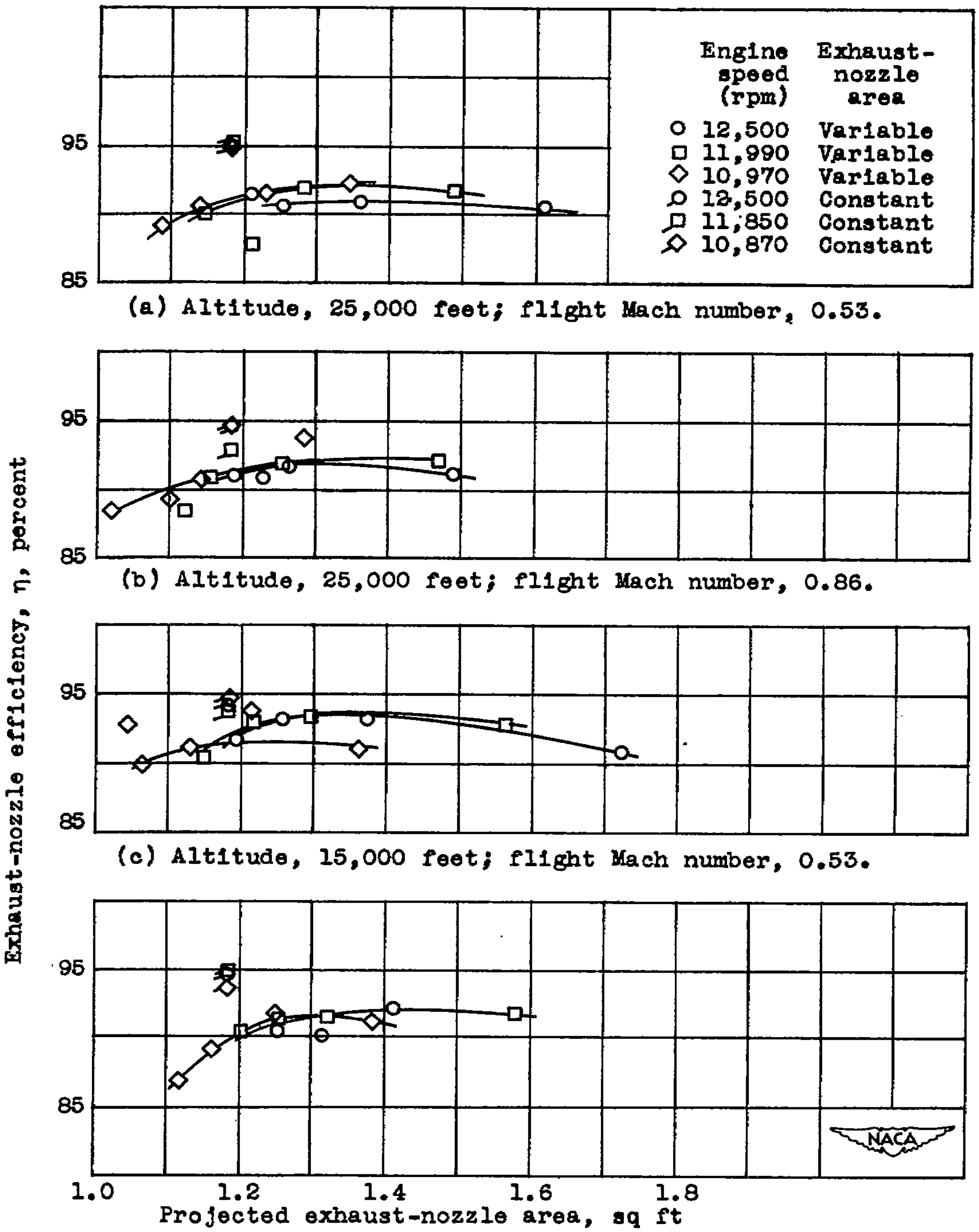


Figure 5. - Exhaust-nozzle efficiency for variable- and constant-area nozzles.

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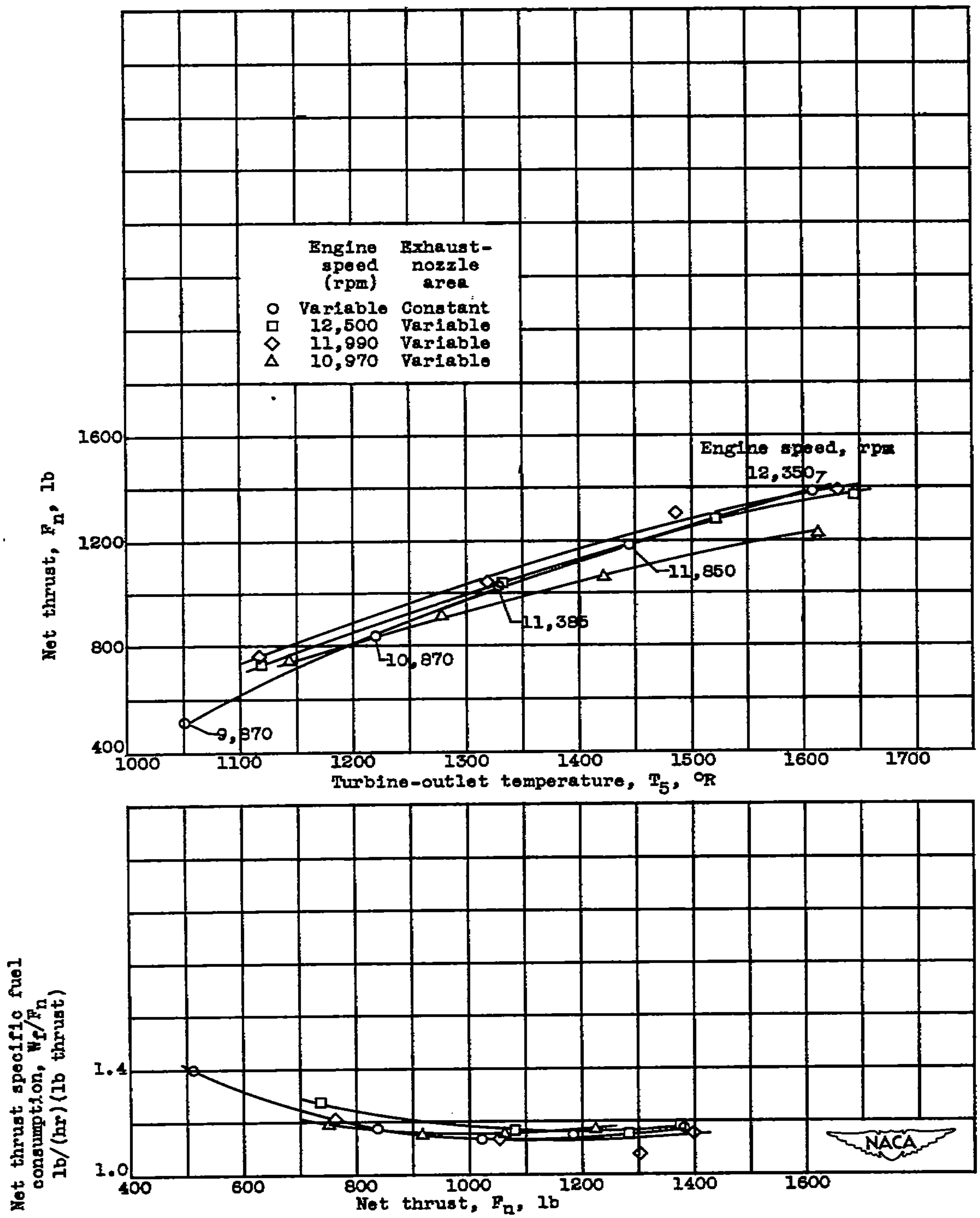
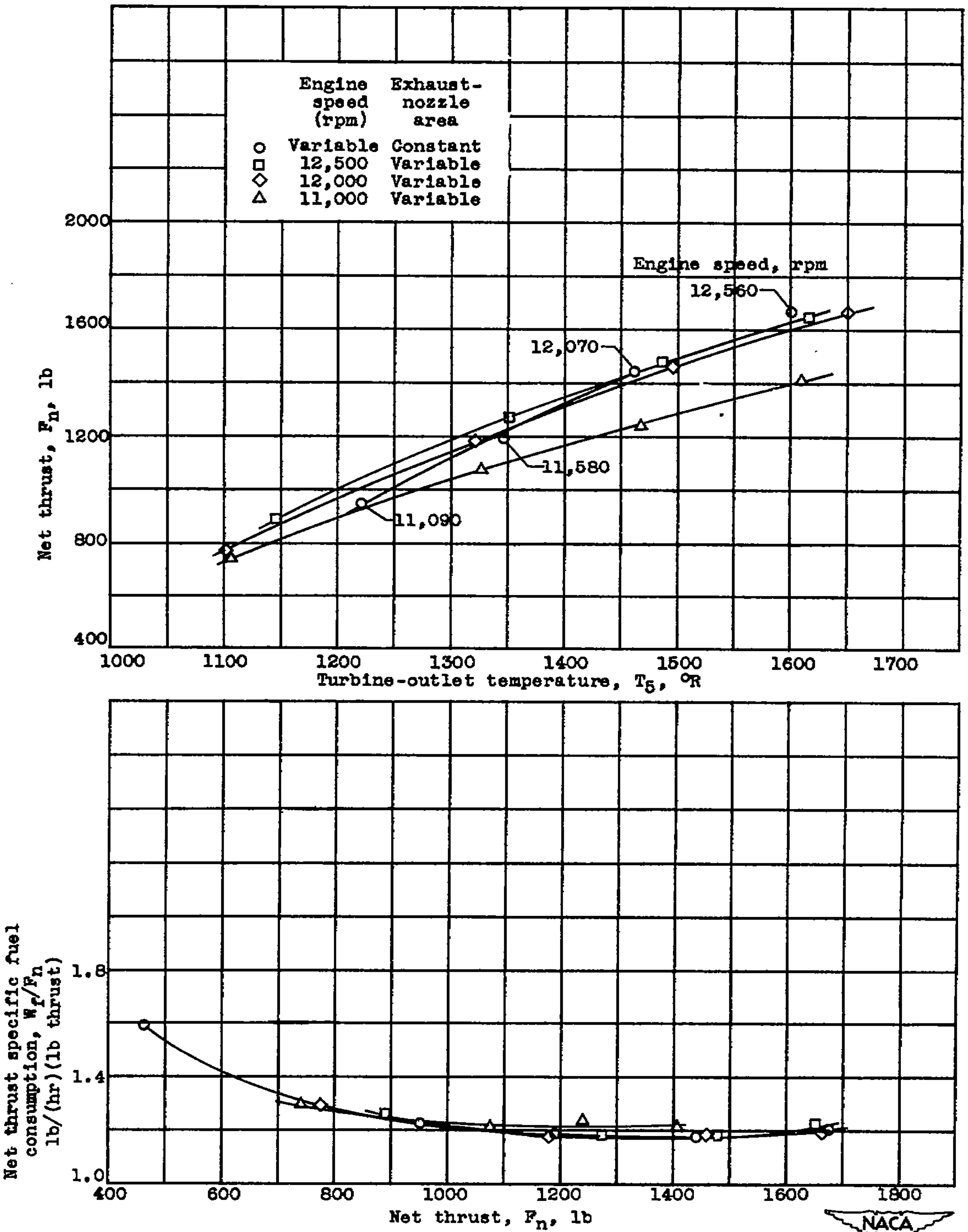


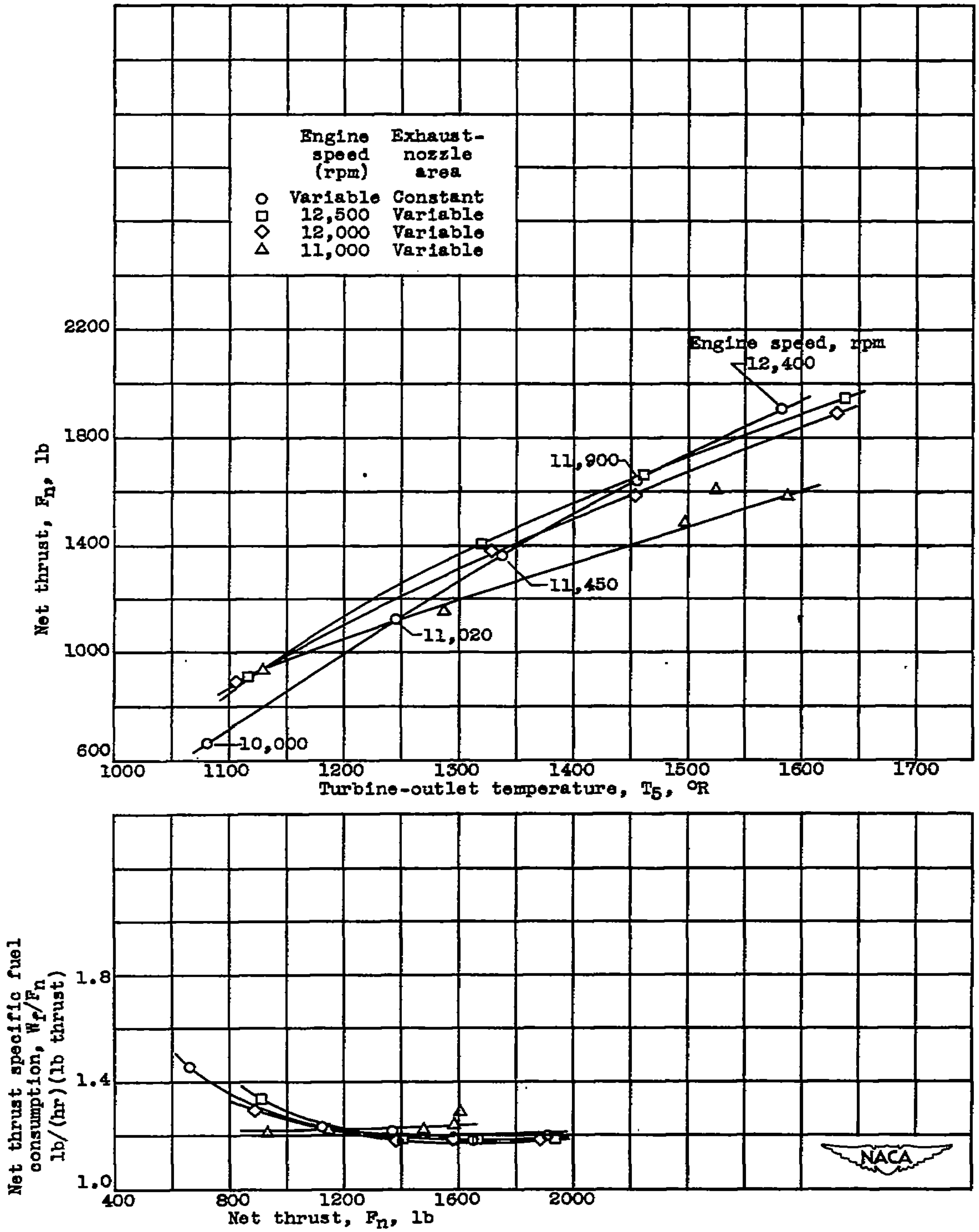
(a) Altitude, 25,000 feet; flight Mach number, 0.53.

Figure 6. - Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for assumed exhaust-nozzle efficiency of 100 percent.



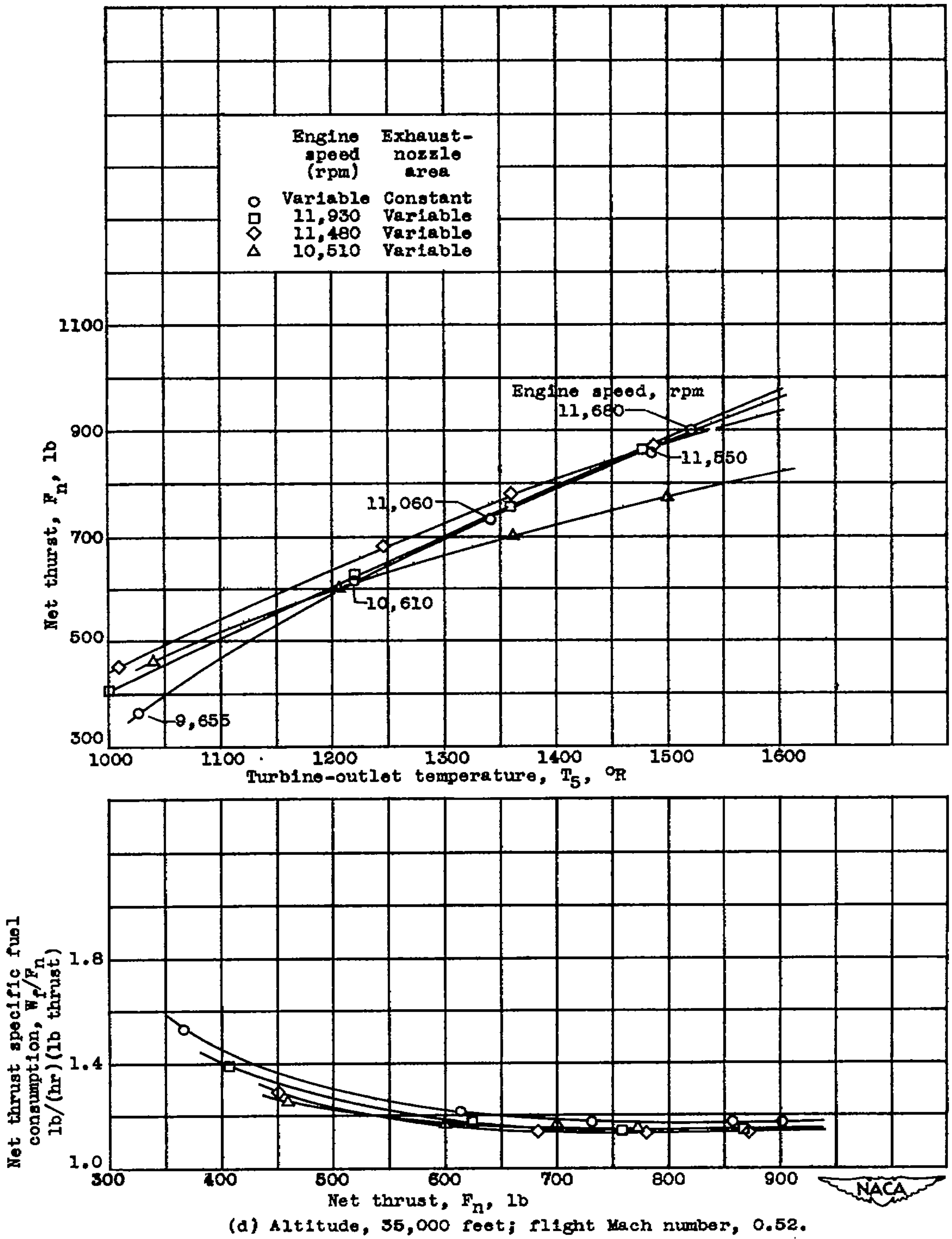
(b) Altitude, 25,000 feet; flight Mach number, 0.86.

Figure 6. - Continued. Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for assumed exhaust-nozzle efficiency of 100 percent.



(c) Altitude, 15,000 feet; flight Mach number, 0.53.

Figure 6. - Continued. Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for assumed exhaust-nozzle efficiency of 100 percent.



(d) Altitude, 35,000 feet; flight Mach number, 0.52.

Figure 6. - Concluded. Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for assumed exhaust-nozzle efficiency of 100 percent.

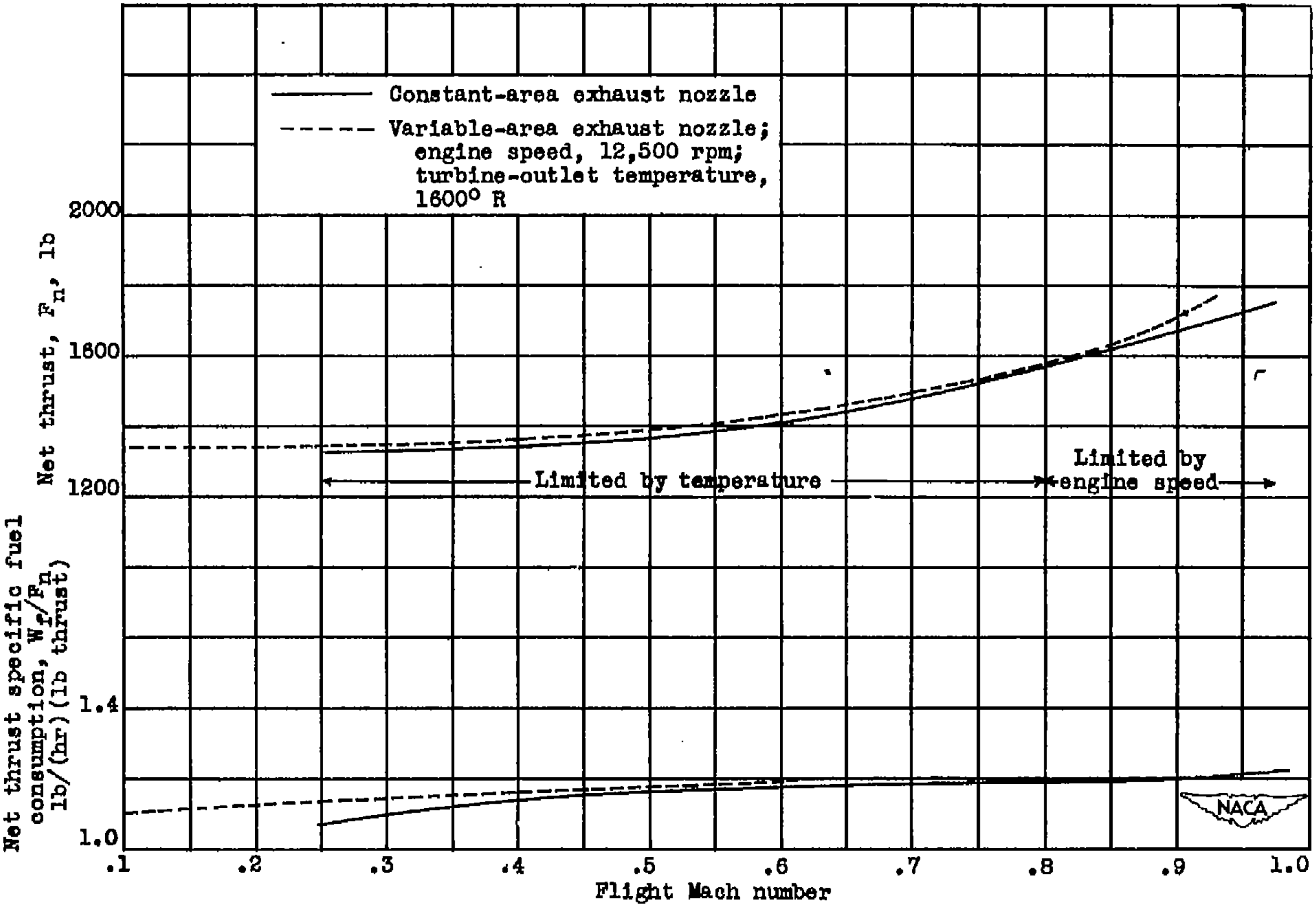
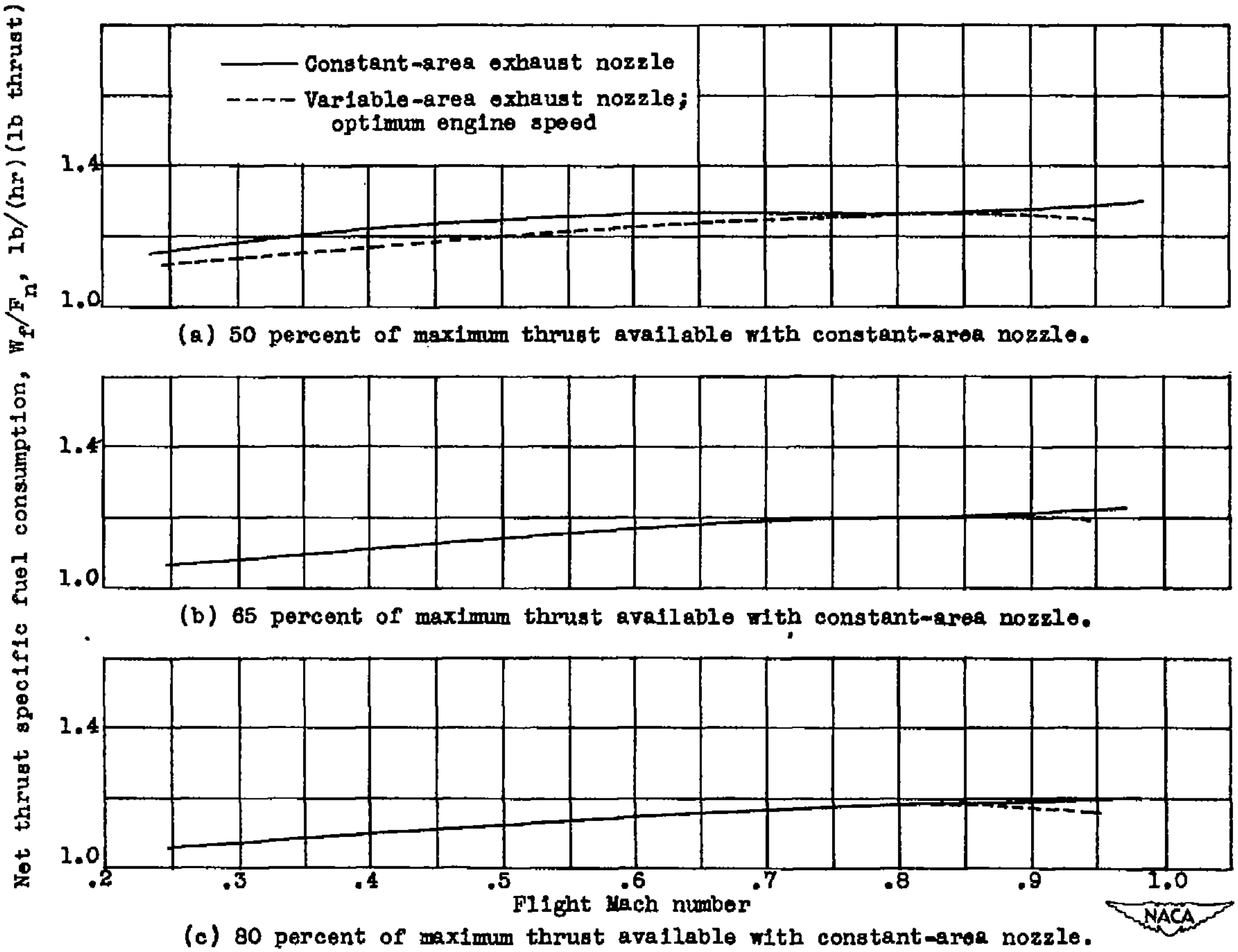


Figure 7. - Variation of net thrust and specific fuel consumption with flight Mach number for assumed exhaust-nozzle efficiency of 100 percent. Altitude, 25,000 feet.



(a) 50 percent of maximum thrust available with constant-area nozzle.

(b) 65 percent of maximum thrust available with constant-area nozzle.

(c) 80 percent of maximum thrust available with constant-area nozzle.

Figure 8. - Variation of specific fuel consumption with flight Mach number at reduced thrust values for assumed exhaust-nozzle efficiency of 100 percent. Altitude, 25,000 feet.

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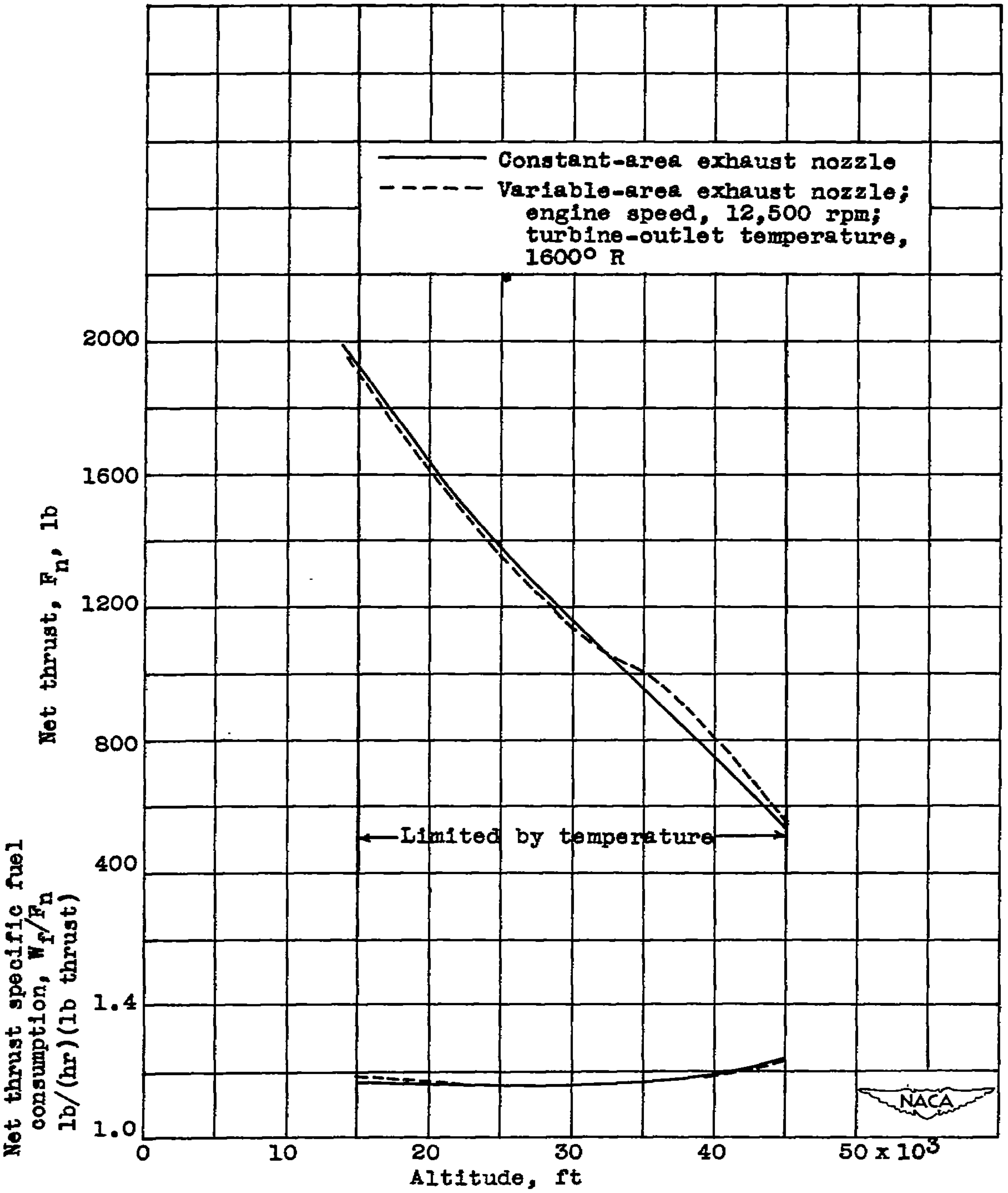
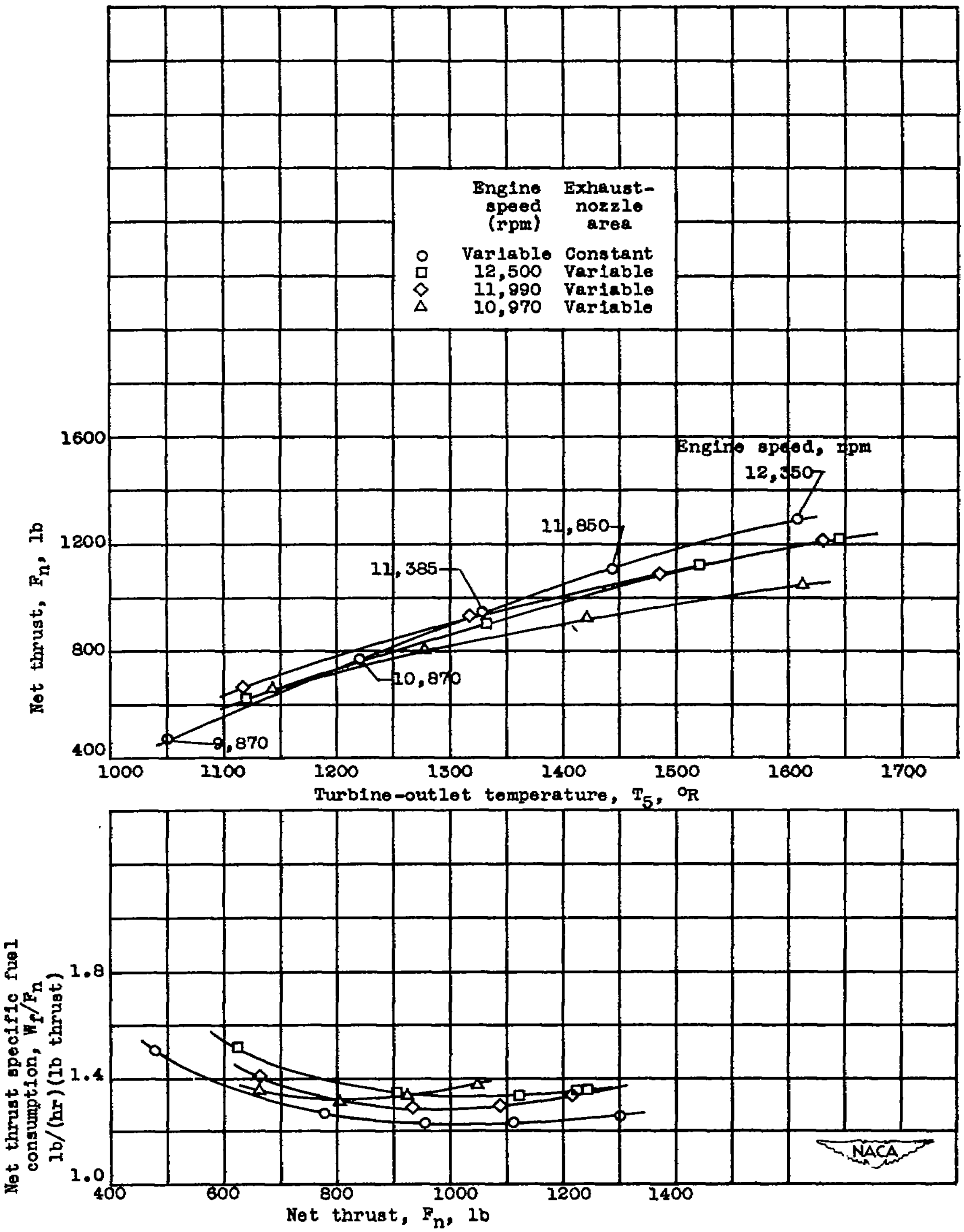


Figure 9. - Variation of net thrust and specific fuel consumption with altitude for assumed exhaust-nozzle efficiency of 100 percent. Approximate flight Mach number, 0.53.



(a) Altitude, 25,000 feet; flight Mach number, 0.53.

Figure 10. - Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for actual exhaust-nozzle efficiencies.

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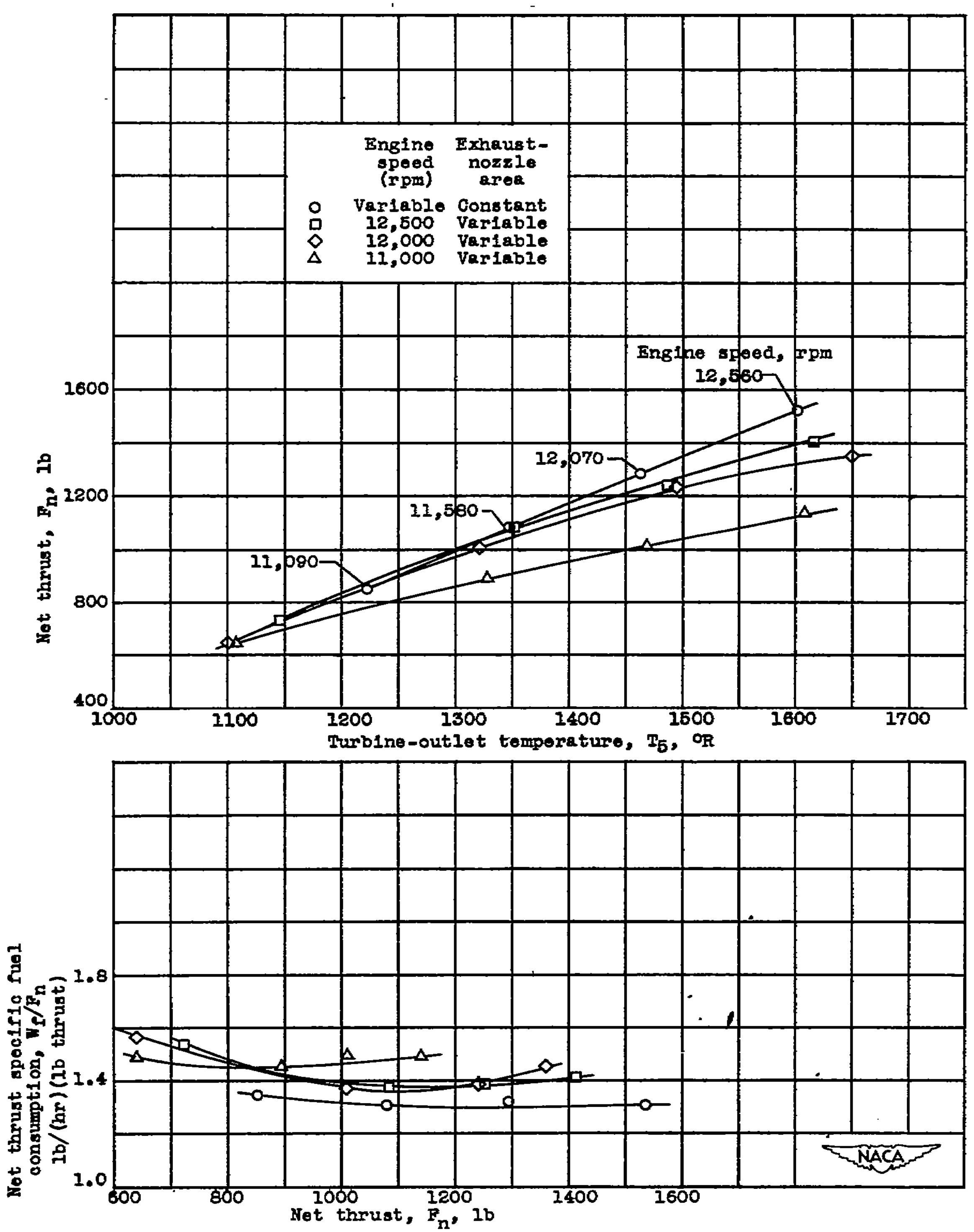
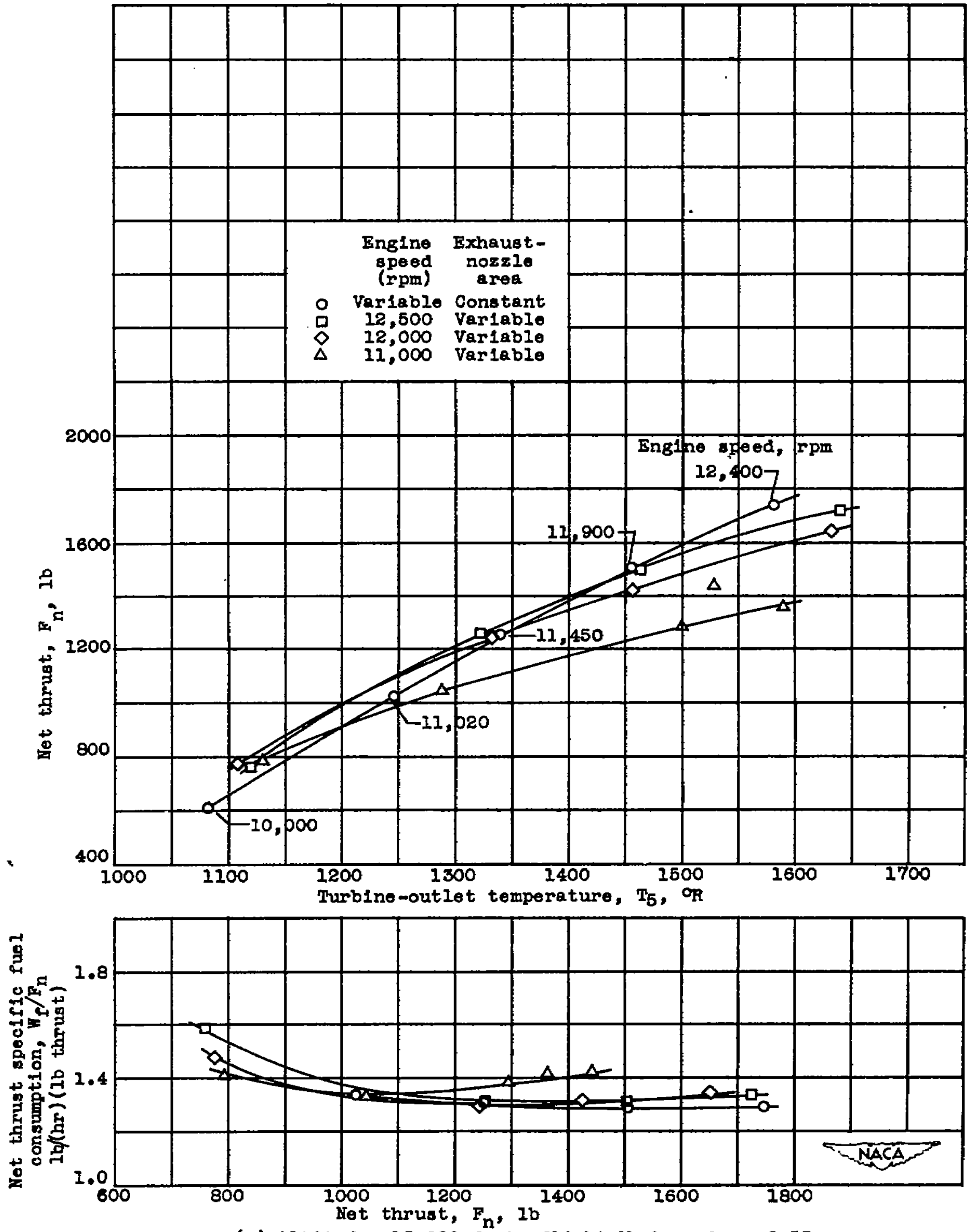


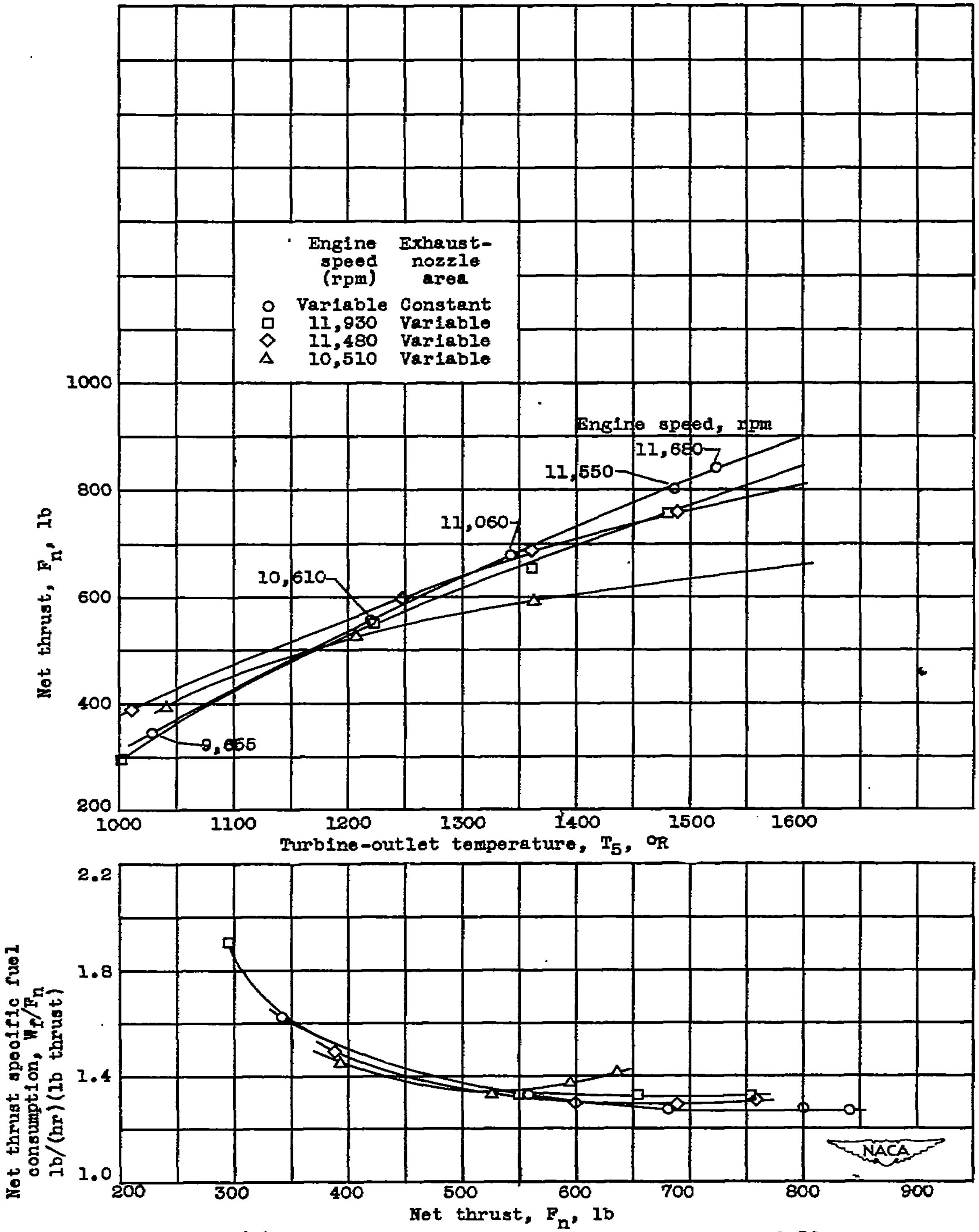
(b) Altitude, 25,000 feet; flight Mach number, 0.86.

Figure 10. - Continued. Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for actual exhaust-nozzle efficiencies.



(c) Altitude, 15,000 feet; flight Mach number, 0.53.

Figure 10. - Continued. Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for actual exhaust-nozzle efficiencies.



(d) Altitude, 35,000 feet; flight Mach number, 0.52.

Figure 10. - Concluded. Variation of net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust for actual exhaust-nozzle efficiencies.

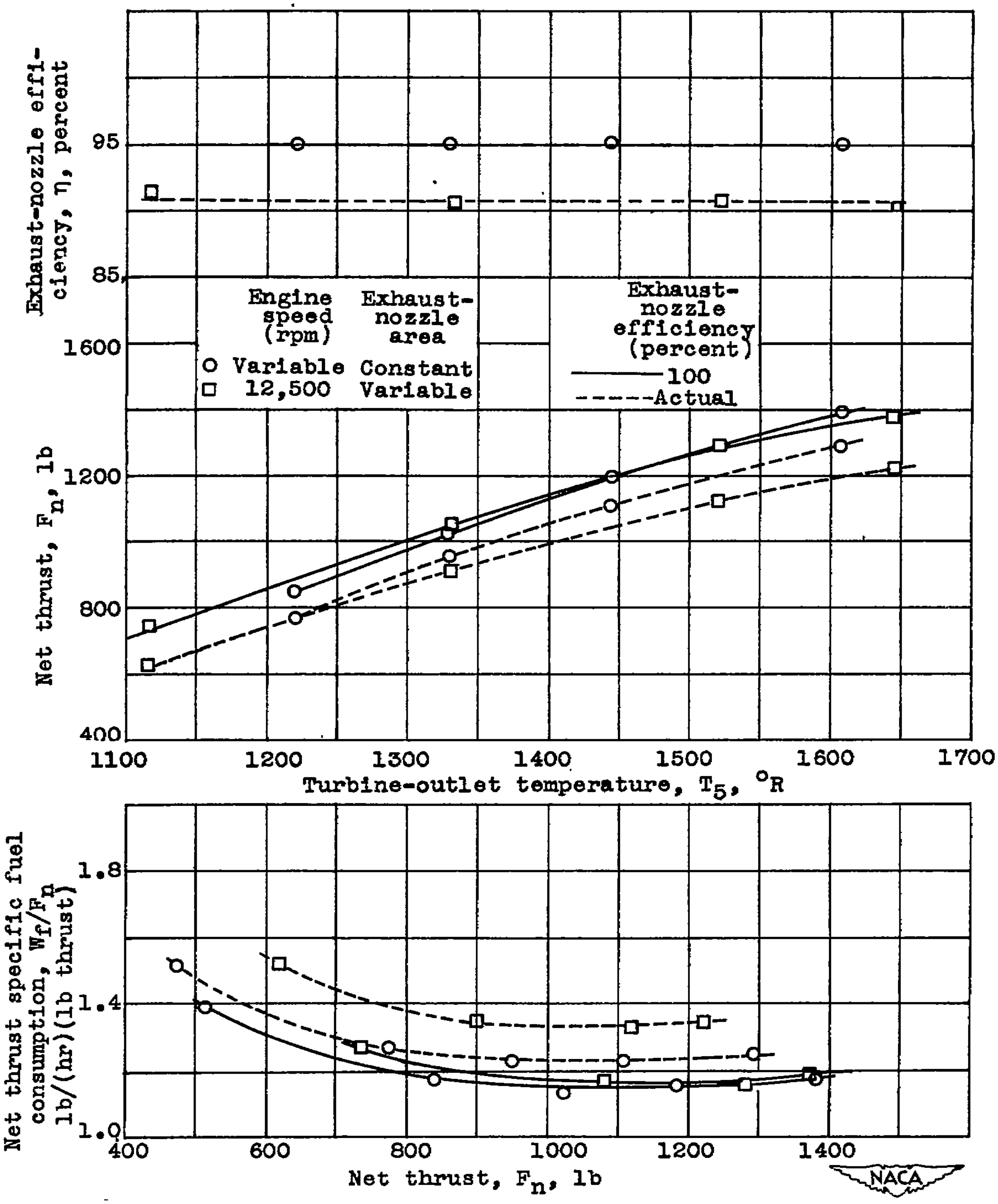


Figure 11. - Variation of exhaust-nozzle efficiency and net thrust with turbine-outlet temperature and of specific fuel consumption with net thrust. Altitude, 25,000 feet; flight Mach number, 0.53.

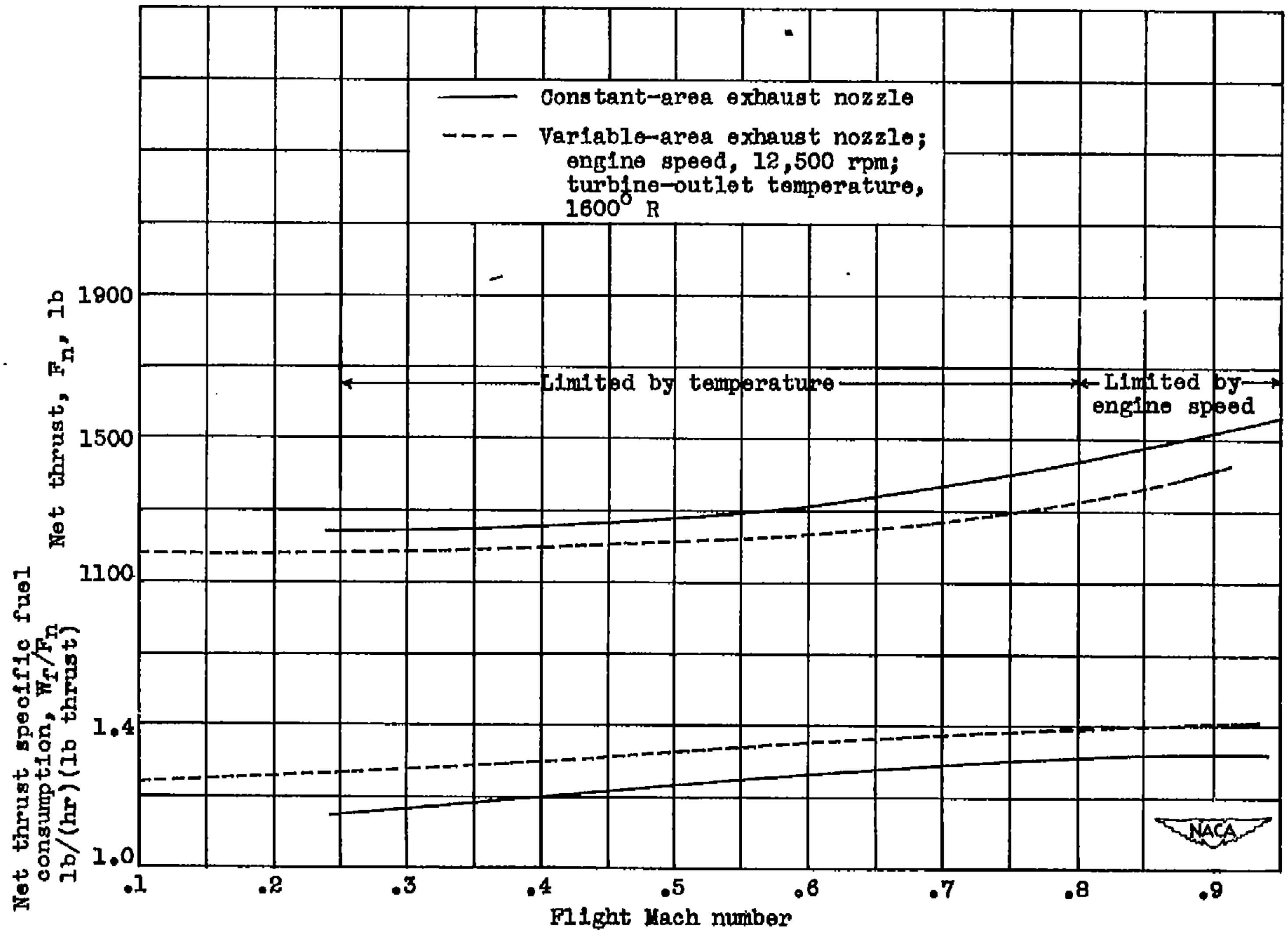
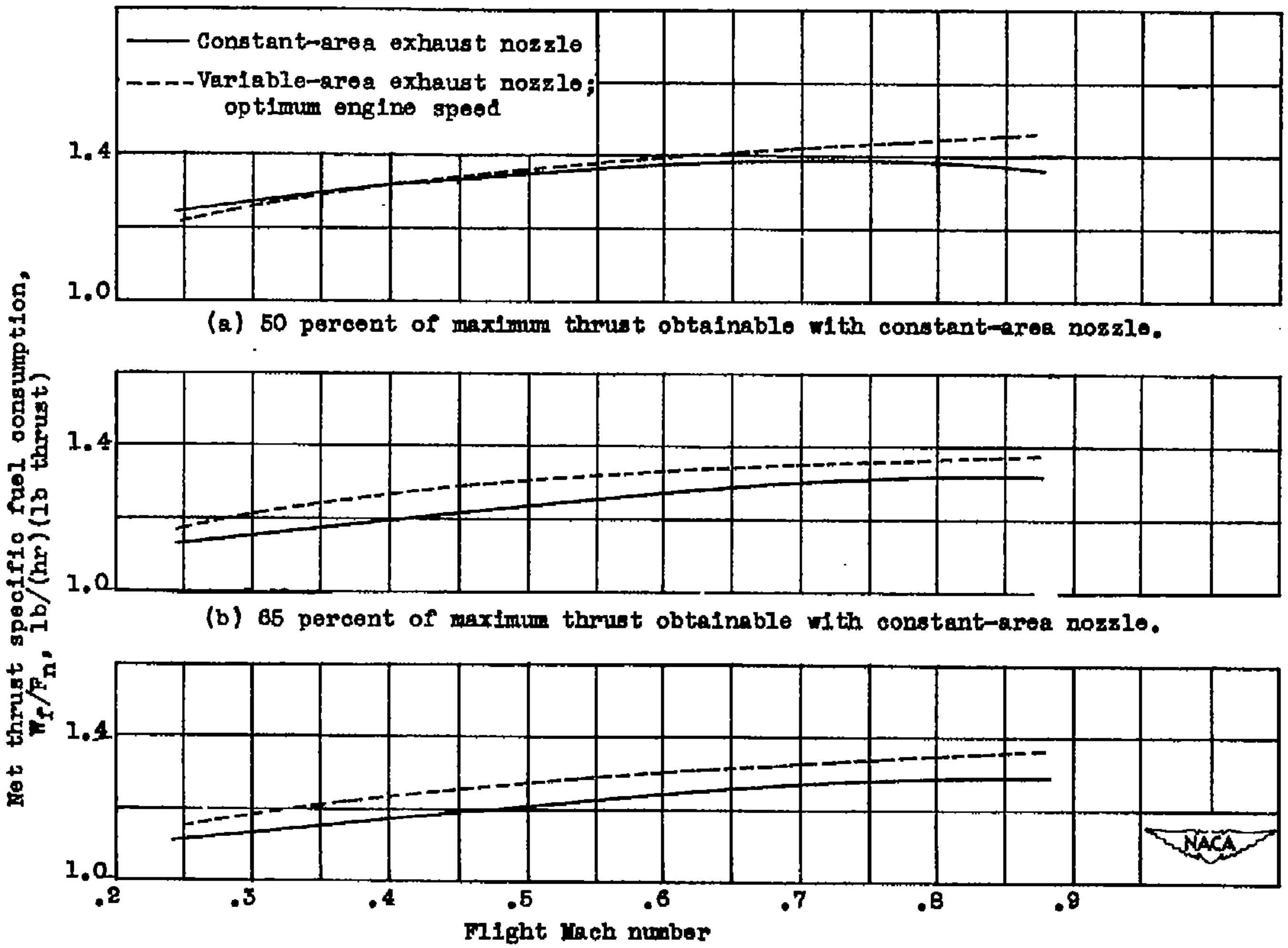


Figure 12. - Variation of net thrust and specific fuel consumption with flight Mach number for actual exhaust-nozzle efficiencies. Altitude, 25,000 feet.



(a) 50 percent of maximum thrust obtainable with constant-area nozzle.

(b) 65 percent of maximum thrust obtainable with constant-area nozzle.

(c) 80 percent of maximum thrust obtainable with constant-area nozzle.

Figure 13. - Variation of specific fuel consumption with flight Mach number at reduced thrust values for actual exhaust-nozzle efficiencies. Altitude, 25,000 feet.

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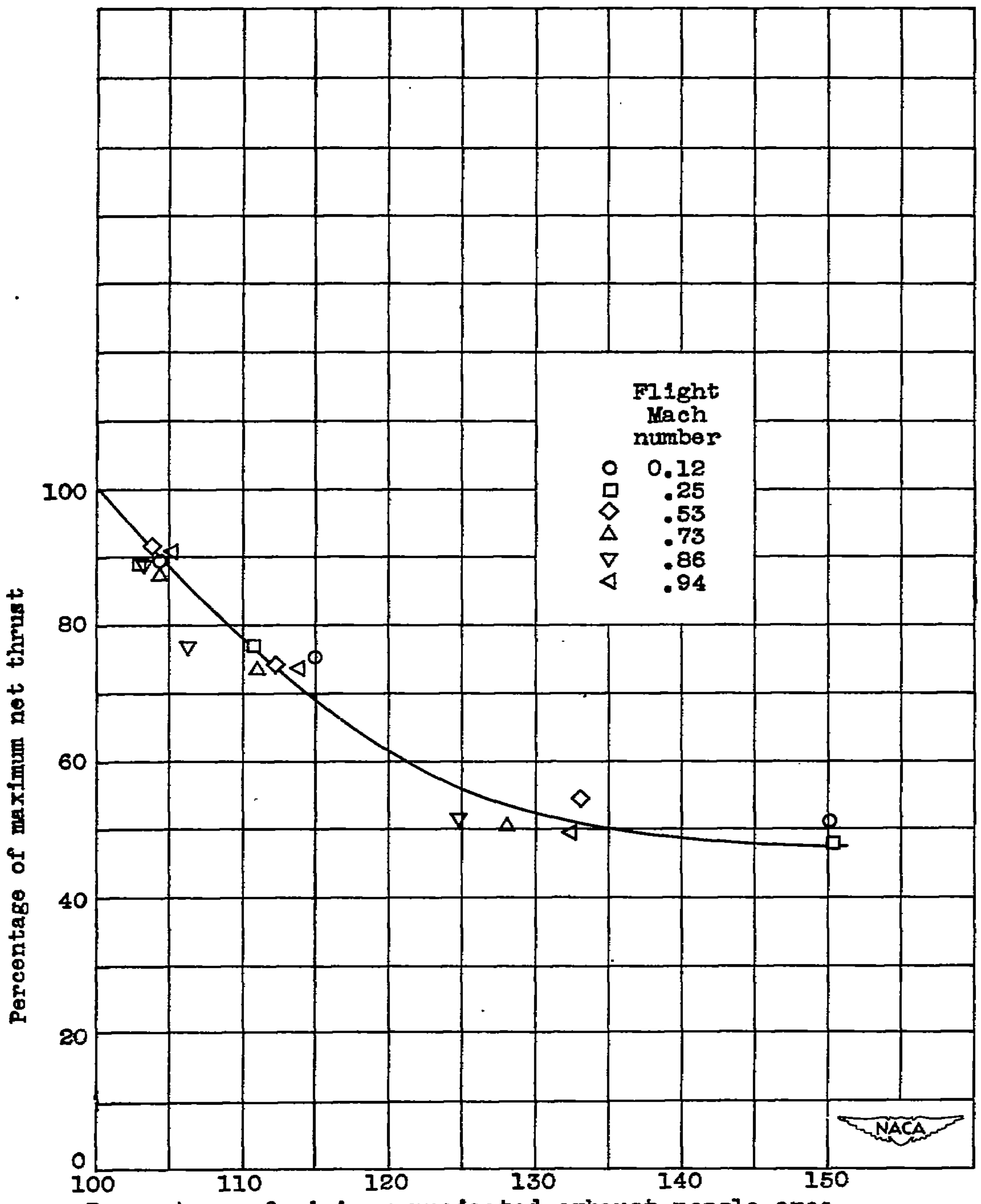

Figure 14. - Variation of net thrust with projected exhaust-nozzle area. Engine speed, 12,500 rpm; altitude, 25,000 feet.

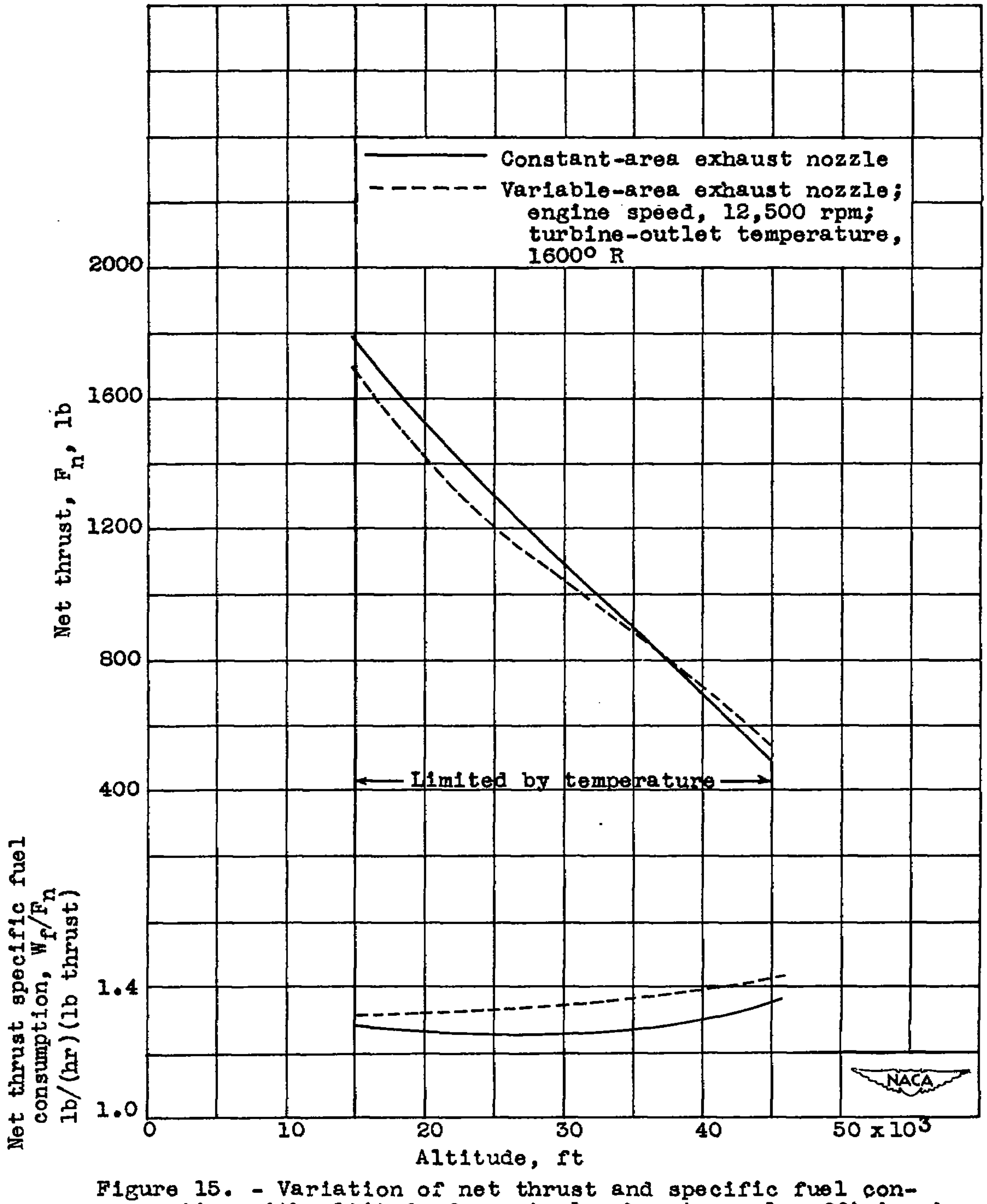

Figure 15. - Variation of net thrust and specific fuel consumption with altitude for actual exhaust-nozzle efficiencies. Approximate flight Mach number, 0.53.

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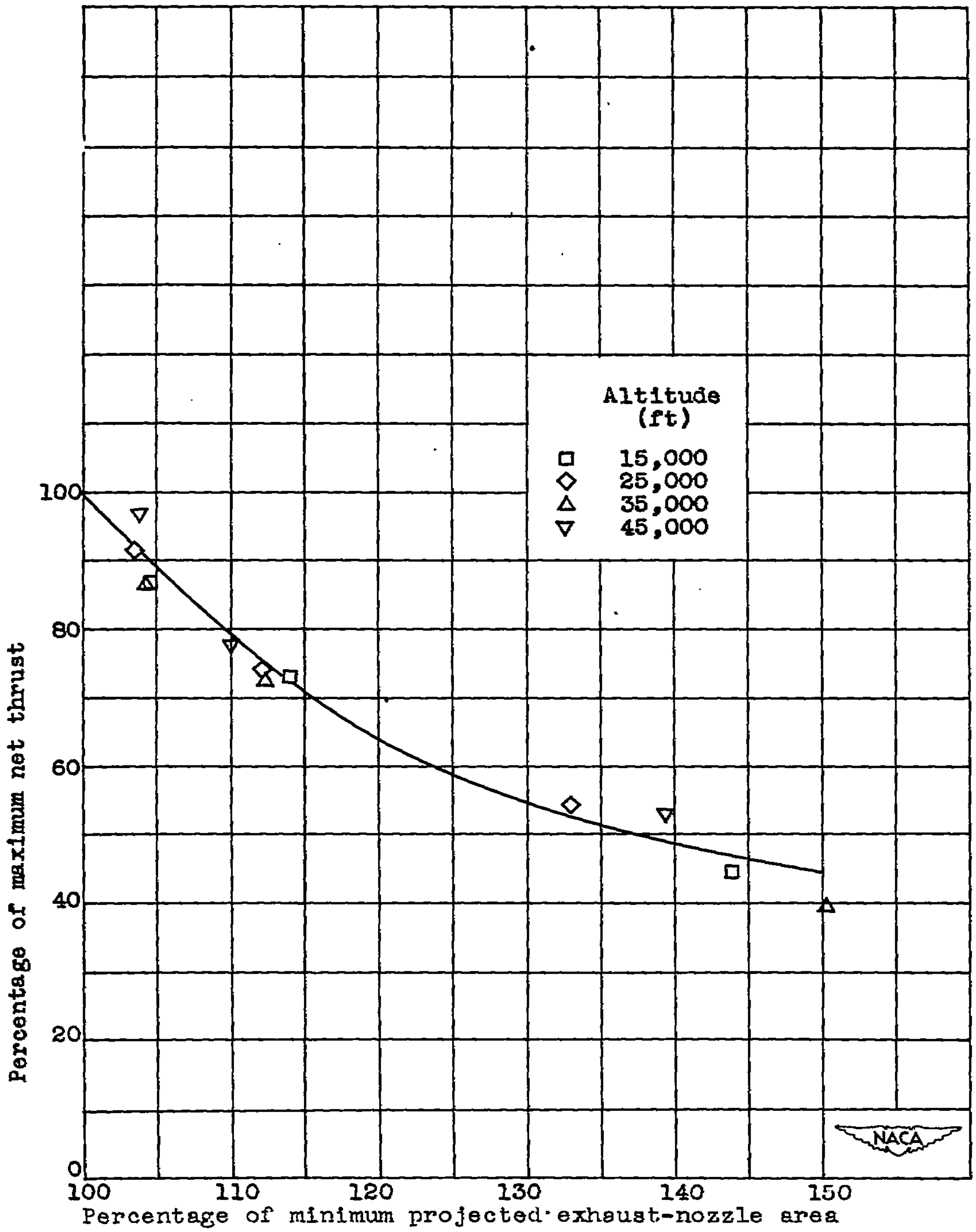

Figure 16. - Variation of net thrust with projected exhaust-nozzle area. Engine speed, 12,500 rpm; approximate flight Mach number, 0.53.